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VOLUME I

FINAL REPORT
PROJECT 1

MANUFACTURE OF LOW CARBON ASTROLOY TURBINE DISK SHAPES
BY HOT ISOSTATIC PRESSING

BY

R. D. ENG
D. J. EVANS

MARCH 1978

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TURBINE DISK SHAPES BY HOT ISOSTATIC
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16. Abstract Project 1 of a five-year cooperative Government/Industry effort, Materials in Advanced Turbine Engines (MATE), was conducted to demonstrate container technology and establish manufacturing procedures for fabricating direct Hot Isostatic Pressing (HIP) of low carbon Astroloy to ultrasonic disk shapes. The goals of the project were to achieve a reduction in material input weight by 54.5 kg (120 lbs) and cost by 20% for net sonic inspection shapes. The approach used in the program consisted of five tasks: Task I established the HIP processing procedures including powder manufacture and handling, container design and fabrication, and HIP consolidation techniques by manufacturing five HIP disks. Based upon dimensional analysis of the first three disks, container technology was refined by modifying container tooling which resulted in closer conformity of the HIP surfaces to the sonic shape. Task II finish-machined one disk for engine demonstration testing. Task III characterized the microstructure, chemistry and mechanical properties of two HIP low carbon Astroloy disks produced under Task I. Task IV subjected one disk to a ground base experimental engine test, and Task V analyzed and compared the results of HIP low carbon Astroloy to conventionally forged Waspaloy®. Results of Project 1 showed that the mechanical properties of direct HIP low carbon Astroloy exceeded all property goals and that the objectives of reduction in material input weight and reduction in cost were achieved.					
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FOREWORD

This report was prepared for the National Aeronautics and Space Administration, Lewis Research Center, under Contract NAS3-20072. It presents the results of a program conducted to establish manufacturing methods to produce hot isostatically pressed (HIP) low carbon Astroloy turbine disks that are ultrasonically inspectable, with properties comparable to conventionally forged Waspaloy®.

Appreciation is expressed for the contributions made by D.L. Ruckle and D.A. Grey who initiated and conducted early portions of this program.

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1.0 SUMMARY

The purpose of this program was to demonstrate container technology and establish manufacturing procedures necessary to fabricate direct HIP low carbon Astroloy to ultrasonic disk shapes for commercial engine use, while reducing input material weight by 54.5 Kg (120 lbs.) and cost by 20%.

Task I established the HIP processing procedures including powder manufacture and handling, container design and fabrication, and HIP consolidation techniques by manufacturing five HIP disks. The disk shape containers were filled with powder under vacuum ($<15\mu$) and then hot vacuum degassed at 316°C (600°F) until a vacuum level of 10^{-5} torr was achieved. HIP consolidation was conducted at $1213 \pm 14^{\circ}\text{C}$ ($2215 \pm 25^{\circ}\text{F}$)/103 MPa (15 ksi)/3 hrs. Inspection of each disk included microstructural (thermally induced porosity tests), ultrasonic, dimensional, chemical and mechanical property analyses. Microstructural evaluation to differentiate between porosity due to hollow particles and porosity due to container failure was conducted to interpret the results of the TIP test. Ultrasonic inspection determined that HIP sonic disk shapes with as-heat treated surfaces can be inspected to detect to a sensitivity of 0.04 cm (1/64 in.) while only defects of 0.119 cm (3/64 in.) or greater can be detected for conventionally forged Waspaloy[®] with machined surfaces.

An essential feature of Task I was the refinement of container technology to achieve net sonic HIP shapes. Based upon the dimensional analysis of an initial group of three disks, the container tooling was modified for a final group of two disks to achieve closer conformity of the HIP surfaces (0.25 cm/0.10 in.) to the sonic shape. Tensile, stress-rupture, and creep property goals (comparable to conventionally forged Waspaloy[®]) were exceeded for specimens removed from the integral test coupon ring of each disk.

Task II finish-machined one direct HIP low carbon Astroloy disk for subsequent engine testing. The machinability of direct HIP low carbon Astroloy was similar to conventionally forged Waspaloy[®] in lathe turning (rough and finish), milling, drilling, reaming, and broaching operations.

Task III characterized the mechanical properties and microstructures of two HIP low carbon Astroloy disks. Tensile, stress-rupture, and creep property goals (comparable to conventionally forged Waspaloy[®]) were exceeded. A design lower limit curve was established for notched ($K_t = 2.5$) low cycle fatigue properties. The microstructure of HIP low carbon Astroloy was characterized by optical and electron replica microscopy. The microstructure consists of matrix gamma, minor phases of borides and carbides, as well as precipitated gamma-prime of various sizes and morphologies depending upon the heat treatment step. Extensive interstitial oxygen analysis including two round-robin analyses revealed considerable scatter in reported oxygen content depending upon the gas standard used for calibration.

Task IV subjected one HIP low carbon Astroloy disk to a ground-base experimental engine test. The engine test conditions as well as a post test analysis of the HIP disk is reported separately in Volume II (CR-135410).

Task V analyzed and compared all the results of HIP low carbon Astroloy to conventionally forged Waspaloy[®]. The mechanical properties of direct HIP low carbon Astroloy exceeded all property goals. The objectives of reduction in material input weight and reduction in cost were achieved.

2.0 INTRODUCTION

BACKGROUND

Advanced aircraft turbine engines expected to enter commercial service in the 1980 to 1985 time period will have performance, cost, and weight requirements that will necessitate the use of advanced materials technologies in their construction. A number of technologies, which potentially meet these needs, have been identified and are currently in various stages of development. To accelerate the development of selected material technologies to the point where they can be verified through engine testing, a five-year cooperative Government/Industry effort, Materials In Advanced Turbine Engines (MATE), has been initiated under NASA sponsorship. The MATE effort was sub-divided into specific materials technology programs.

Hot isostatic press manufacture of Astroloy turbine disk shapes was the materials technology selected for the MATE Project 1 program.

Lower engine weight and higher operating temperatures needed to meet the higher thrust-to-weight requirements of advanced gas turbine engines has necessitated the development of advanced turbine disk materials with greater strength and cyclic life capabilities. To provide these capabilities, disk alloys must contain increased amounts of gamma prime forming elements (Ni_3Al , Ti). While this approach results in alloys with improved properties, obtaining these properties in large diameter engine disks fabricated from cast +forged billets is both difficult and costly. This is due to the chemical inhomogeneity in large ingots caused by the segregation during solidification which is inherent in these highly alloyed superalloys. Use of powder metallurgical processing techniques is one way to produce disks from these advanced disk materials in order to ensure compositional homogeneity and, thereby, mechanical property uniformity. An approach that can satisfy the uniform properties requirements is the direct hot isostatically pressing powder into disk shapes. By reducing raw material input, and thus the amount of excess material which must be machined to yield a finished part, it was anticipated that a reduction in material input weight and cost was possible for net sonic inspection shapes.

At Pratt & Whitney Aircraft, direct HIP low carbon Astroloy was demonstrated to have the potential to exceed the mechanical properties of conventionally forged Waspaloy[®]. Therefore, the low carbon Astroloy composition was selected for evaluation. An analysis of the existing forging configuration of a JT8D first stage turbine indicated that HIP consolidating to the sonic shape could reduce material requirements by 54.5 kg (120 lbs.) and cost by 20 percent.

This volume presents the technical effort accomplished in Project 1. FEDD Category 2 data which includes an engine test program and post test analysis of a direct HIP turbine disk is reported in Volume II of this Project 1 Final Report (CR-135410).

PROGRAM SCOPE

The following tasks were accomplished under this program.

Task I established the manufacturing methods necessary to produce JT8D first stage turbine disks by hot isostatic pressing low carbon Astroloy powder of the composition shown in

Table I to net sonic shapes. Five disk shapes with a final target shape shown in Figure 1 were produced by the Udimet Powder Division of Special Metals Corporation. Preliminary mechanical properties were determined for the integral test coupon ring of each disk. The target properties are shown in Table II. These property goals are comparable to conventionlly forged Waspaloy®.

TABLE I
COMPOSITIONAL RANGE OF LOW CARBON ASTROLOY
POWDER AND POWDER METAL COMPONENTS

Element:	Weight Percent																PPM			
	Ni	C	Mn	S	P	Si	Cr	Co	Mo	Ti	Al	B	Zr	W	Fe	Cu	Pb	Bi	O	N
Maximum:	R* 0.06	0.15	0.015	0.015	0.015	0.20	16	18	5.5	3.65	4.15	0.03	0.06	0.05	0.50	0.10	10	0.5	100	50
Minimum:	R* 0.02	—	—	—	—	—	14	16	4.5	3.35	3.85	0.02	—	—	—	—	—	—	—	—

R* = remainder

TABLE II
MECHANICAL PROPERTY REQUIREMENTS
FOR HIP LOW CARBON ASTROLOY POWDER DISKS

	0.2% Yield Strength MPa (ksi)	Ultimate Tensile Strength MPa (ksi)	Elongation (%)	Reduction in Area (%)
RT Tensile	862 (125)	1241 (180)	15	18
538°C (1000°F) Tensile	758 (110)	1103 (160)	15	18
732°C/552 MPa Stress-Rupture (1350°F/80 ksi)	Life 23 hrs.		Elongation (%) 8	
704°C/510 MPa Creep (1300°F/74 ksi)	Time to 0.1% Elongation 100 hrs.			

Task II finish-machined one disk for an engine demonstration test.

Task III concurrently characterized the microstructure, chemistry and mechanical properties of the disks produced in Task I.

Task IV subjected one disk to sea level experimental engine demonstration testing.

Task V provided the post test analysis including visual, fluorescent penetrant, and dimensional inspection of the turbine disk tested in Task IV and analyzed results of the entire Project I.

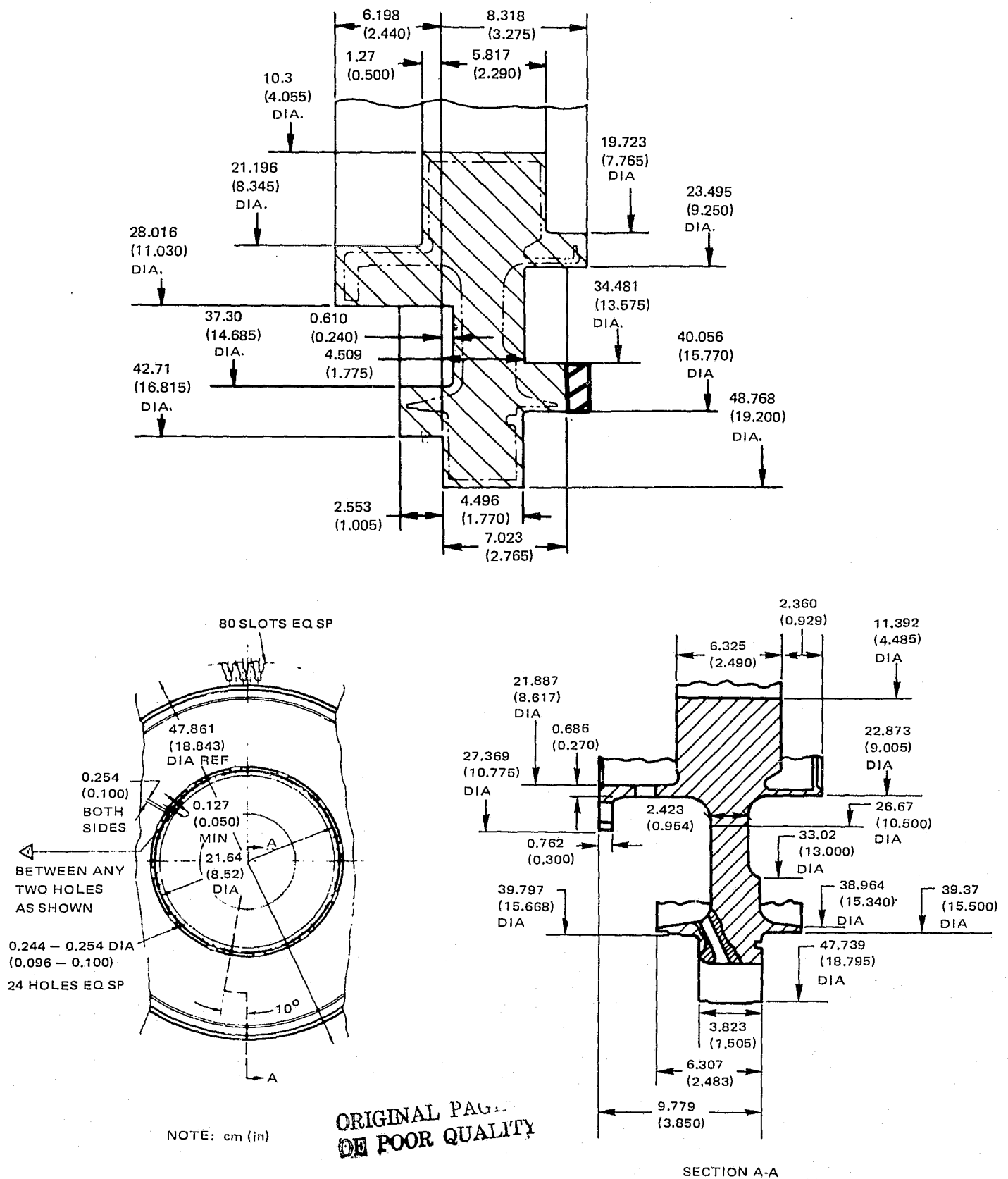


Figure 1 JT8D First Stage Turbine Disk Shown in the Net Sonic Configuration (Upper) and Finished Configuration (Lower). Location of integral test ring is shown on sonic shapes in dark reversed cross hatching.

3.0 TASK I—HOT ISOSTATIC PRESS (HIP) PROCESSING

Task I established the manufacturing methods to produce direct HIP + heat treated low carbon Astroloy JT8D first stage turbine disks. Procedures were established for the following areas:

- Powder manufacture and storage
- Disk shape container design and fabrication
- Powder outgassing and transport from storage to disk shape container
- HIP consolidation cycle

A flow chart outlining the processing and evaluation sequence is shown in Figure 2. A group of three disks was initially HIP and inspected. Based upon the dimensional analysis of the initial group of disks, the tooling was modified for the final group of two disks to bring the as-HIP surfaces closer to target sonic shape. Preliminary chemical and mechanical properties were determined for the integral test coupon ring of each disk.

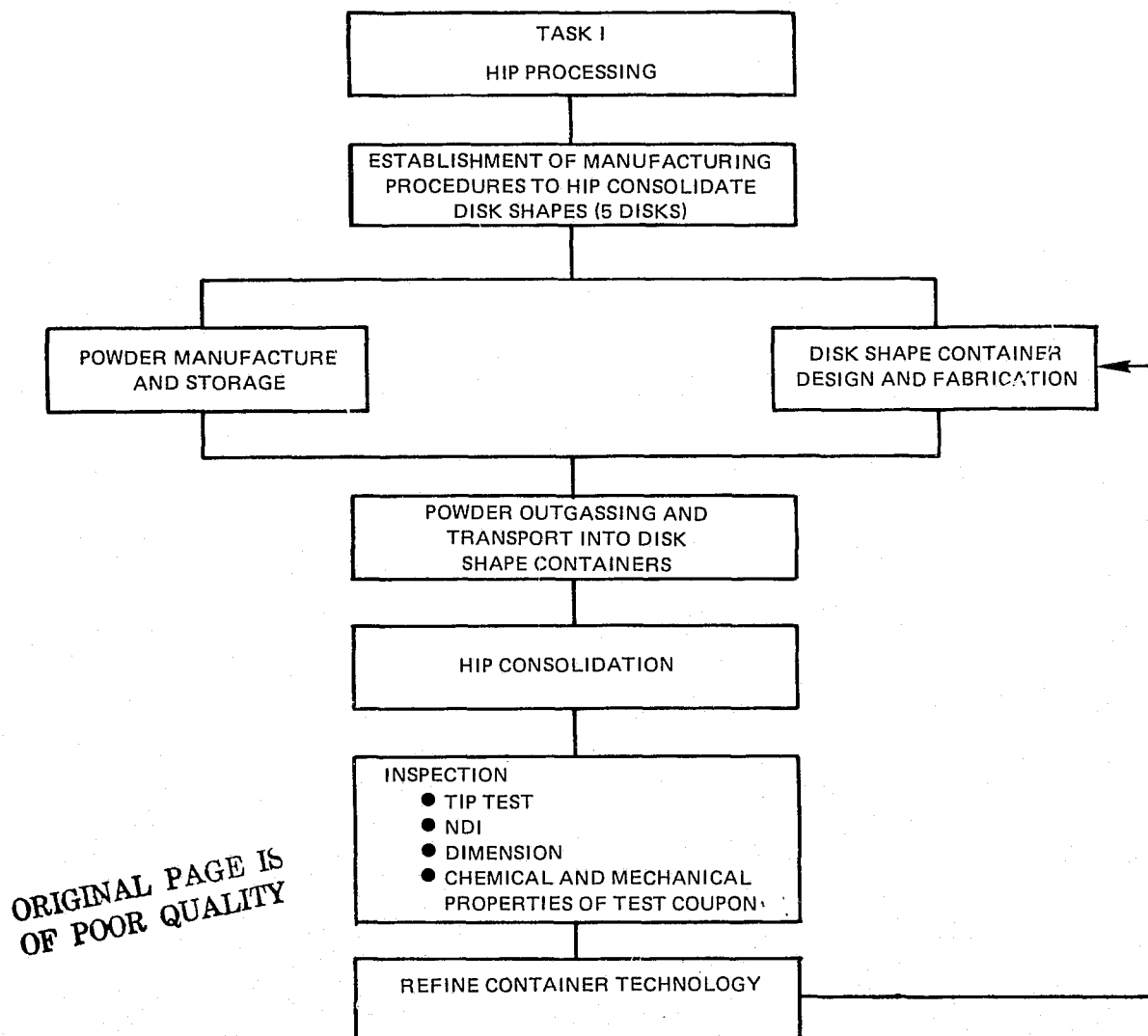


Figure 2 Flow Chart of Hot Isostatic Press (HIP) Processing

POWDER MANUFACTURE

Low carbon Astroloy vacuum induction melted master alloy ingots used for conversion into powder were supplied by Teledyne-Allvac. The chemistry of this master alloy, heat code 2382, is given in Table III. The ingots were converted by argon atomization at the Princeton, Kentucky facility of the UDIMET Powder Div. of Special Metals Corp. The atomized powder was handled in inert (argon) atmosphere at all times. The powder was classified with the -80 mesh portion blended into two lots, B/N 75026 (1209 Kg/2660 lbs) and 75027 (868 Kg/1910 lbs), for evaluation in Project 1. The chemistry and sieve analysis of these two blend lots are given in Tables IV and V, respectively. All powder was stored in sealed containers under argon gas.

Scanning electron microscopy was performed on a 90% B/N 75026 — 10% B/N 75027 mixture of powder to further characterize the powder. Figure 3 shows the dendritic structure of the solidified powder as well as a number of irregularly shaped particles. Optical microscopy of a microsection of the powder revealed less than 0.3% spherical porosity associated with hollow particles as shown in Figure 4. These hollow particles contain gas which is invariably entrapped in some of the rapidly solidified particles during inert gas atomization.

TABLE III

LOW CARBON ASTROLOY MASTER ALLOY CHEMISTRY HEAT CODE 2382

	Aim	Actual Ladle Analysis
C	.02 - .06	.029
Cr	14.0 - 16.0	14.80
Co	16.0 - 18.0	16.80
Mo	4.5 - 5.5	4.90
W	< .05	—
Al	3.85 - 4.15	4.10
Ti	3.35 - 3.65	3.60
B	0.2 - 0.3	.028
Zr	< .06	.01
Cu	< .10	—
Fe	< .50	.06
Ni	Remainder	Remainder
P	< .015	.007
S	< .015	.003
Si	< .20	.05
Mn	< .15	—
Pb	< 10 PPM	< .1 PPM
Bi	< .5 PPM	< .3 PPM
O	< 100 PPM	—
N	< 50 PPM	—

TABLE IV
POWDER BLEND CHEMICAL ANALYSIS

	Aim	BN75027	BN75026
C	.02 - .06	.024	.026
Cr	14.0 - 16.0	14.37	14.17
Co	16.0 - 18.0	17.01	17.41
Mo	4.5 - 5.5	5.30	5.01
W	<.05	.029	.031
Al	3.85 - 4.15	4.07	4.13
Ti	3.35 - 3.65	3.58	3.63
B	0.2 - 0.3	0.21	0.23
Zr	<.06	.002	.002
Cu	<.10	.047	.047
Fe	<.50	.09	.087
Ni	Remainder	Remainder	Remainder
P	<.015	.005	.005
S	<.015	.006	.005
Si	<.20	.018	.019
Mn	<.15	.001	.010
Pb	<10 PPM	<1.0 PPM	<1.0 PPM
Bi	<.5 PPM	<.2 PPM	<.2 PPM
O	<100 PPM	90 PPM	94 PPM
N	<50 PPM	6 PPM	6 PPM

TABLE V
TYPICAL SCREEN ANALYSIS

Mesh	BN75027	BN75026
+80	-0%	-0%
-80 + 100	1.8%	1.5%
-100 + 120	3.9%	3.8%
-120 + 140	5.7%	5.2%
-140 + 170	5.7%	6.3%
-170 + 200	9.2%	9.8%
-200 + 230	6.4%	7.3%
-230 + 270	10.0%	10.8%
-270 + 325	8.4%	7.8%
-325 + 400	11.8%	10.5%
-400 + 500	19.2%	20.1%
-500	17.9%	16.8%

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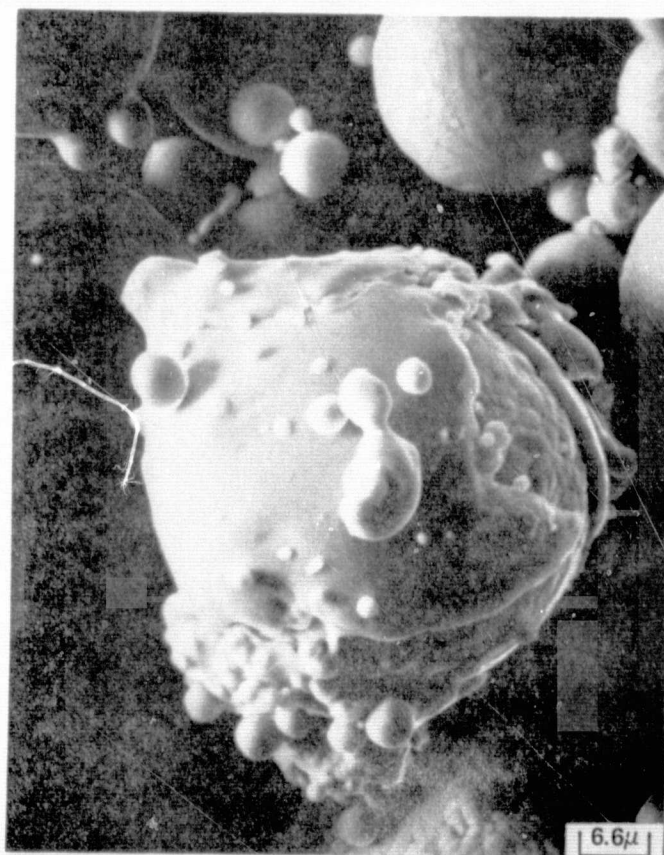
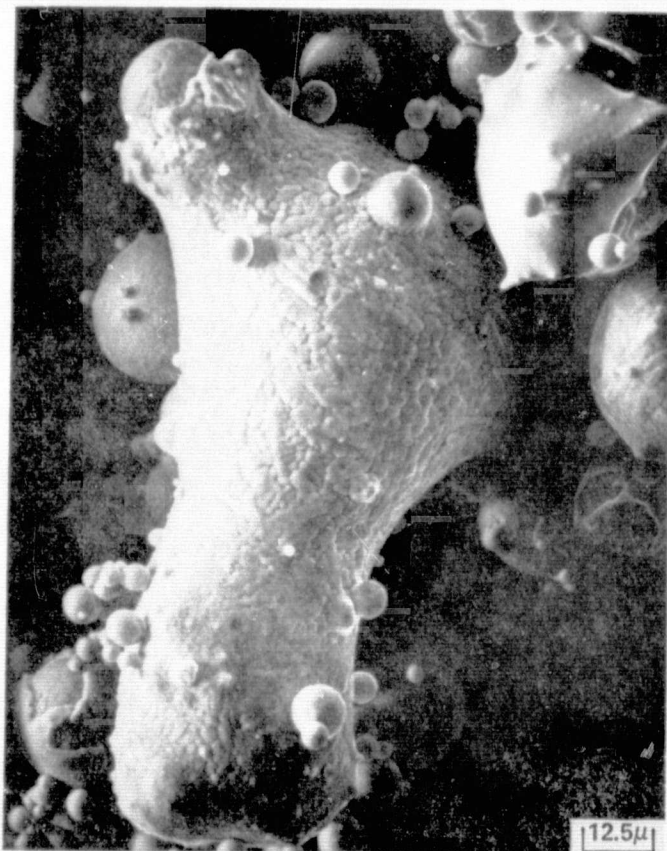
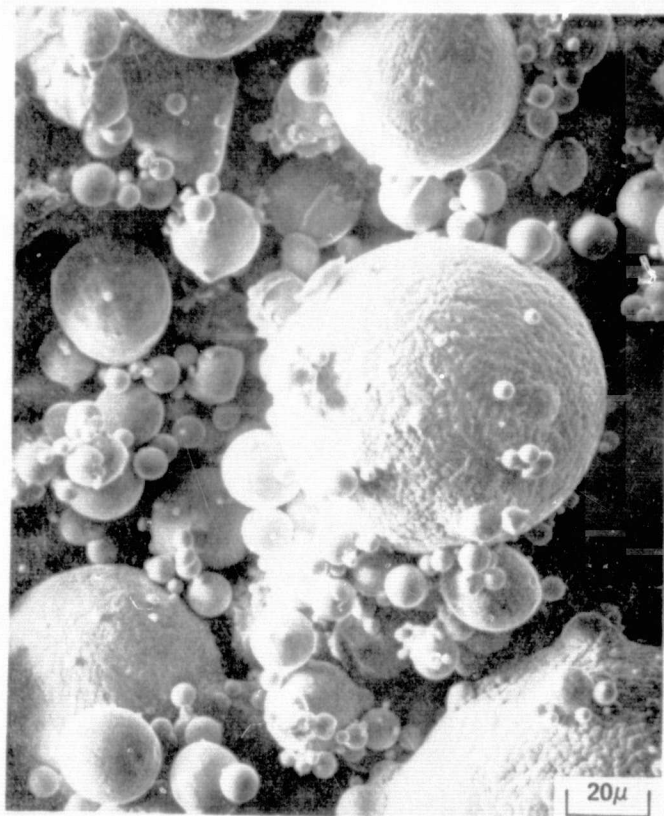
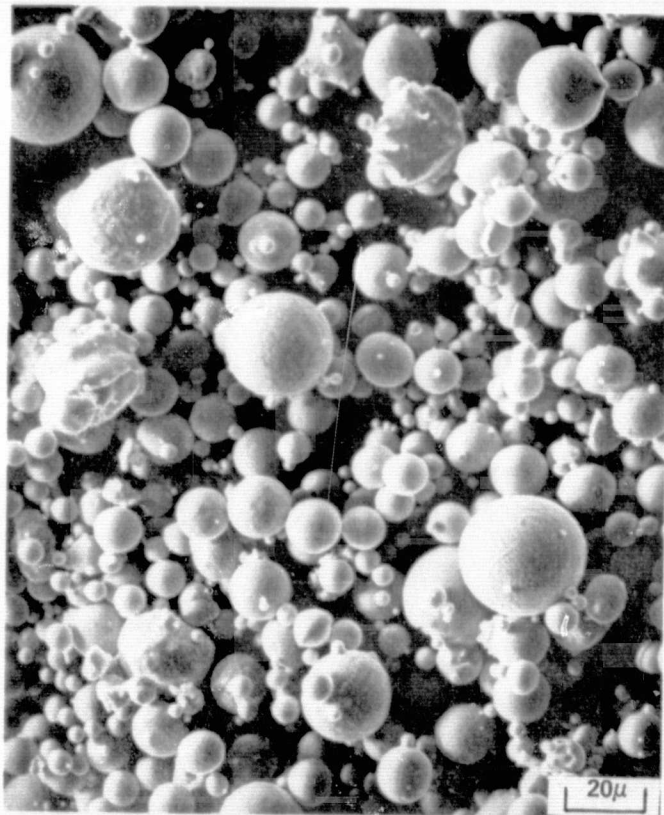


Figure 3 Scanning Electron Micrograph of As-Atomized Low Carbon Astroloy Powder Showing Dendritic Structure of the Solidified Powder as well as some Irregularly Shaped Particles

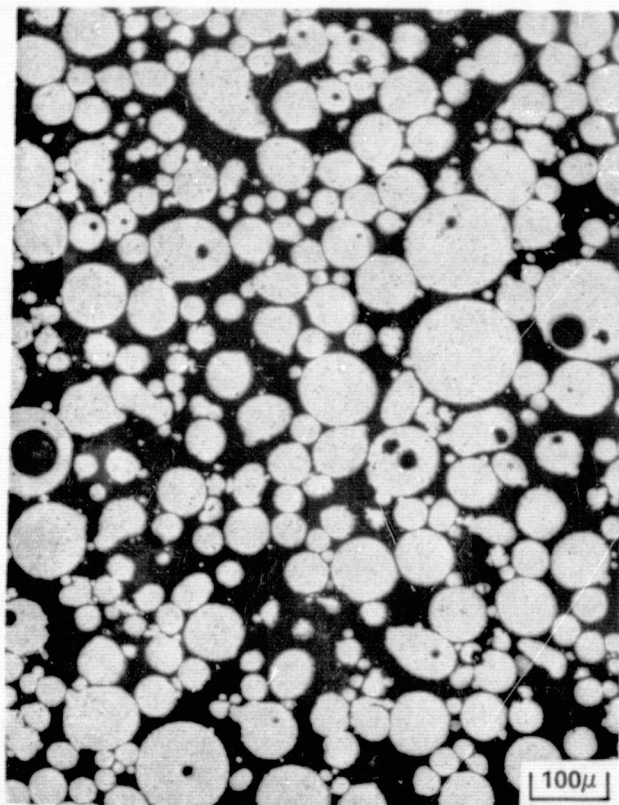


Figure 4 Microsection of Low Carbon Astroloy Powder Showing Less than 0.3% Spherical Porosity

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CONTAINER FABRICATION

The dimensions for three different target disk shapes selected for container construction are given in Table VI. Each disk container was constructed with four-pieces of mild steel material welded together. The front and rear faces of the containers were formed by shear spinning 0.191 cm (0.075 in.) thick SAE 1008 sheet, while 15.2 cm (6 in.) diameter pipe with a 0.63 cm (0.25 in.) wall was used for the bore as shown in Figure 5. The fourth piece was a fill tube which was made of 0.125 cm (0.049 in.) wall, 1.90 cm (0.75 in.) OD seamless SAE 1015 tube. Shear spinning was accomplished in multiple steps utilizing metal tooling.

Immediately prior to welding construction, each container segment was degreased and washed in acetone. Each segment was assembled in a welding fixture and GTA welded at the locations shown in Figure 5. The fill tube was welded to the container using 308 stainless steel filler rod. During welding, the entire container was purged with argon to minimize oxidation of the steel. The assembled containers were leak-checked by pressurizing with 20 psig argon while submersing in a water-soap solution. After a few HIP consolidations (50-1, 50-3, 76-1) were determined to have leaked during the HIP cycle, a visual inspection of a spare container revealed tears associated with subsurface inclusions in the formed SAE 1008 container material. Microstructural analysis of formed sheet metal taken from this same heat of material showed subsurface oxide stringers and several areas on the surface displaying entrapped inclusions aligned parallel to the rolling direction (Figure 6). These inclusions probably contributed to container failure prior to HIP consolidation. A different heat of material, which conformed to AMS 5041 (extra deep drawing) specification, was used for all subsequent containers (disks 80-1 and 80-2). This heat of material survived a transverse 180° flat bend test without cracking or showing evidence of coarse grain.

CONTAINER FILLING

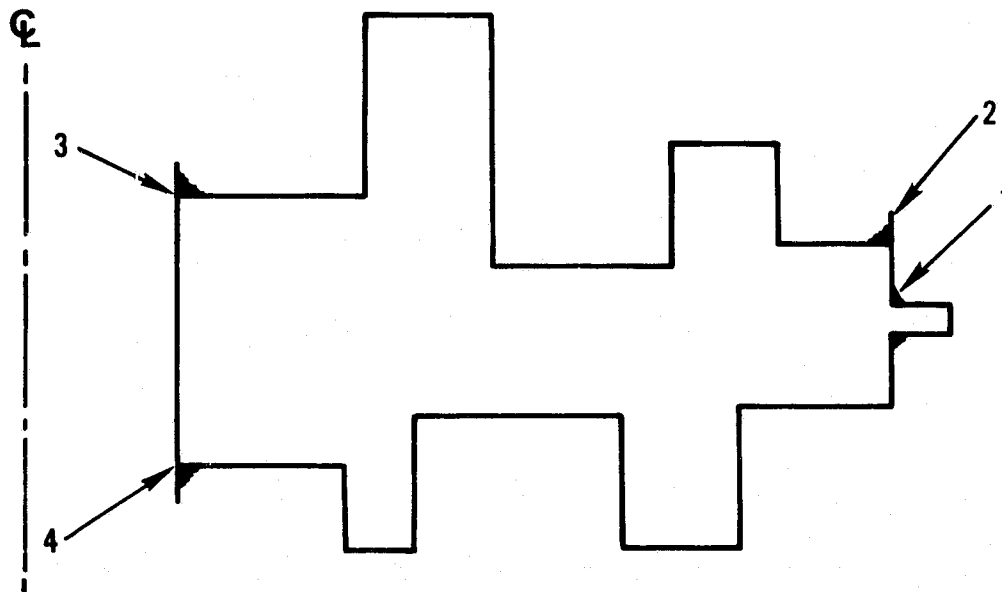
Each container was filled under vacuum with powder using a transport facility shown schematically in Figure 7. The powder was fed into the top of the powder transport facility via a tote bin and evacuated to $<15\mu$ of mercury. As the powder was metered from the storage bin, it was vibrated to expose each individual powder particle for vacuum outgassing. During container filling, the vacuum level in the powder transport facility was maintained at $<15\mu$ of mercury. After each container was filled with powder, the container was valved off to maintain a vacuum and transferred to a station for hot vacuum outgassing at 316°C (600°F) and 10^{-5} torr. After a pressure of 10^{-5} torr was achieved and maintained for at least 12 hours, the container was sealed by crimping and fusion welding of the fill tube. Each disk identity with corresponding powder weight and hot outgassing parameters is given in Table VII. Due to a malfunction in the furnace, disks 50-2 and 50-3 were heated to 243°C (470°F) and 163°C (325°F), respectively. Disk 80-1 was momentarily exposed to atmospheric pressure during transfer to the hot outgassing station because some powder particles were trapped in the valve.

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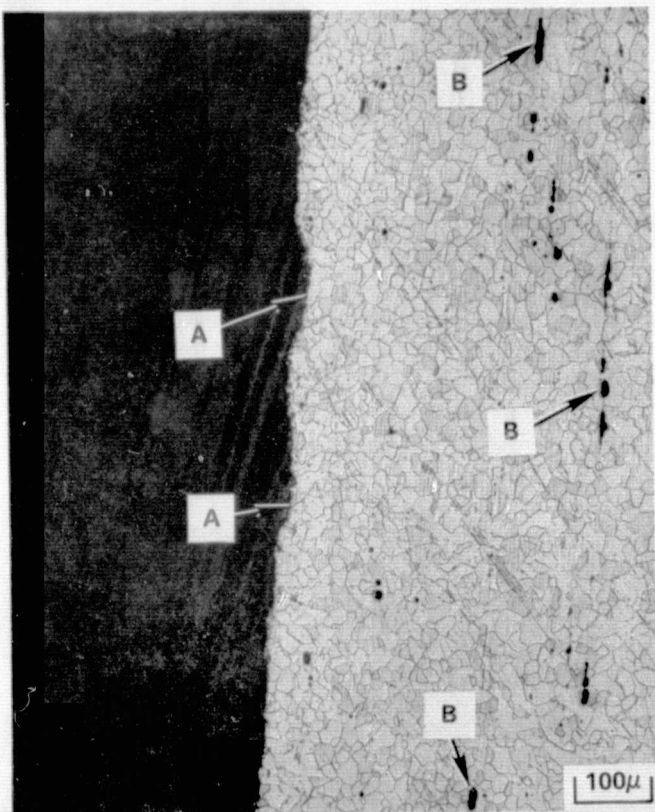


NOTE: cm(in)

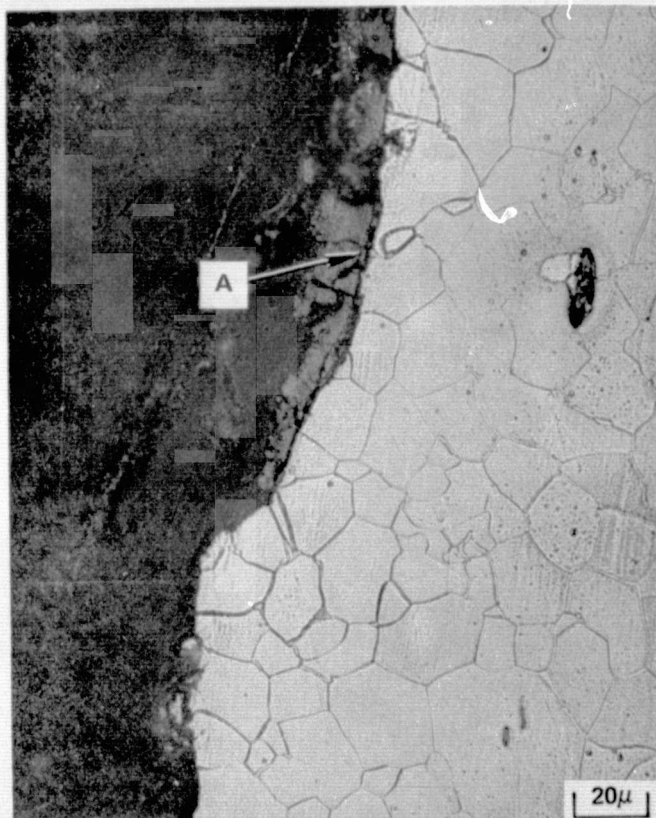
*ALSO TARGET DIMENSIONS FOR FOURTH AND FINAL
ITERATION (i.e., DISKS 76-1, 80-1, 80-2)



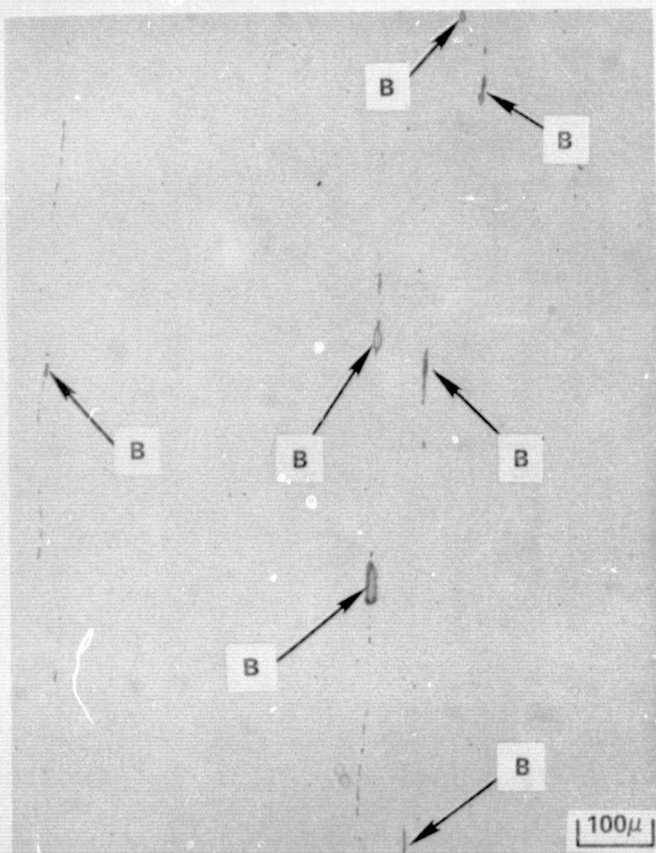
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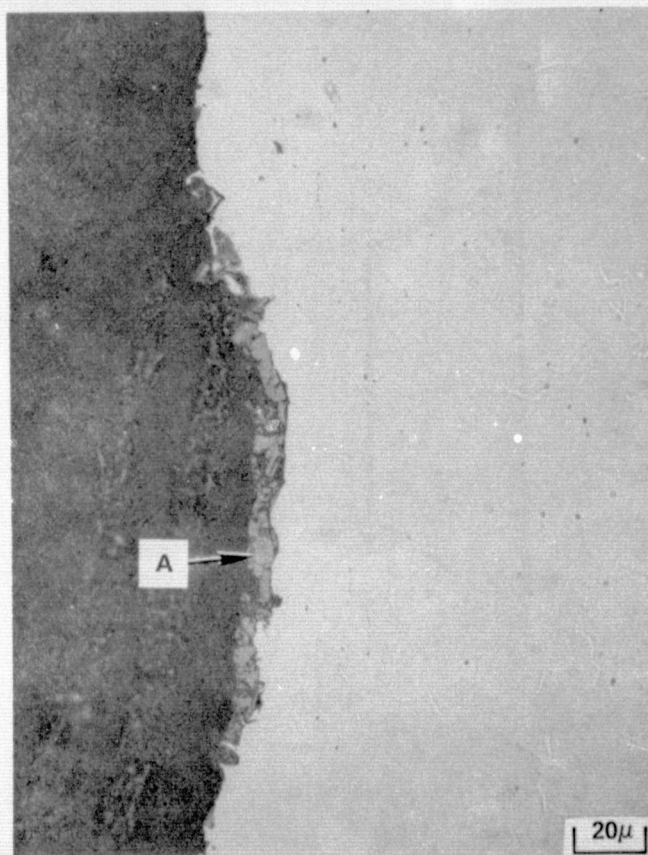


Figure 6 Microstructure of Formed SAE 1008 Sheet Metal Which is the Same Heat of Material Used for Disk 76-1 that Leaked During HIP Consolidation. Note the surface inclusions (A) and large angular particles (B).

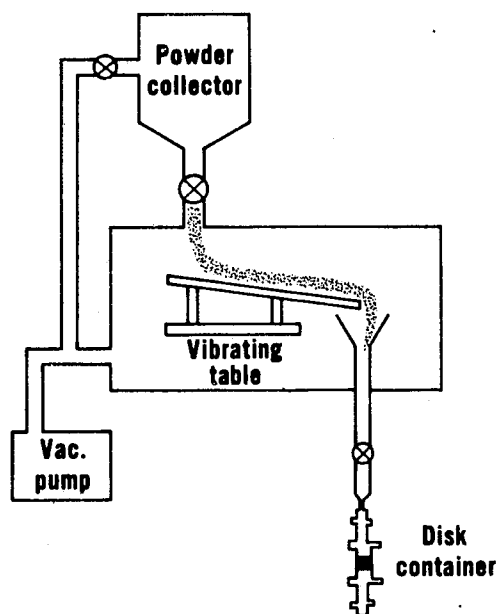


Figure 7 Powder Process Facility

TABLE VII

WEIGHT AND OUTGASSING PARAMETERS FOR EACH DISK

Disk Identification KBI No.	Container (1) Shape	Powder Weight Kg (lbs)	Powder Blend	Temp °C (°F)	Outgassing Parameters	
					Dynamic Pressure, Torr	Leak Rate, Microns/3 Min.
50-1	(1st Iteration)	140.5 (309)	BN75027	316 (600)	2×10^{-5}	10
50-2	(2nd Iteration)	123.6 (272)	BN75027	243 (470)	3×10^{-5}	16
50-3	(3rd Iteration)	118.2 (260)	BN75026	163 (325)	4×10^{-5}	20
58-1	(Mod. 3rd Iteration)	114.1 (251)	BN75026	316 (600)	9×10^{-6}	3
58-2	(Mod. 2nd Iteration)	118.1 (260)	BN75026	316 (600)	1×10^{-5}	5
80-1(2)	Revised Tooling	111.8 (246)	90% BN75026- 1% BN75027	316 (600)	3×10^{-5}	7
80-2	Revised Tooling	113.2 (249)	99% BN75026- 10% BN75027	316 (600)	3.5×10^{-5}	5
76-1	Revised Tooling	113.2 (249)	BN75026	316 (600)	8×10^{-6}	.8

(1) Container target dimensions are given in Table VI.

(2) Vacuum was not maintained during transfer from filling station to outgassing.

HIP CONSOLIDATION AND TIP (THERMALLY INDUCED POROSITY) TESTING

The evacuated, sealed disk containers were HIP consolidated by Kawecki Berylco, Inc. (KBI) Hazelton, Pennsylvania, using the following cycle:

- $1213 \pm 14^{\circ}\text{C}$ ($2215 \pm 25^{\circ}\text{F}$)
- 103 MPa (15 KSI)
- 3 hrs.

A thermally induced porosity (TIP) test was conducted to determine the quality of HIP consolidation. A TIP test consists of a microexamination of a segment (usually the fill tube) of the consolidation which had been exposed to a temperature near the HIP consolidation temperature. The level of porosity is determined by point-count technique. Coalescence of gas during the high temperature exposure of the TIP test enables a determination of the effectiveness of powder outgassing during container filling and the integrity of the container during HIP. Two types of porosity can be observed in the microstructure of a TIP tested specimen. One type is spherical porosity associated with hollow particles containing entrapped inert gas. This gas is invariably entrapped in some of the powder particles upon rapid solidification during inert gas powder atomization. A second type of porosity is observed at the prior particle boundaries (triple points) and is associated with container failure prior to HIP consolidation. Gas which is leaked-in will not permit consolidation of powder particles.

For HIP low carbon Astroloy, the TIP temperature selected was $1204 \pm 6^{\circ}\text{C}$ ($2200^{\circ} \pm 10^{\circ}\text{F}$)/4 hrs/AC. Of the initial set of three disks (50-1, -2, -3), only one disk (50-2) consolidated satisfactorily with $<0.1\%$ porosity associated with hollow particles as determined by TIP tests (Figure 8). The microstructures of TIP tested fill tubes of disks 50-1 and 50-3 revealed porosity at prior particle boundaries (triple points) as shown in Figure 8 indicating that the container failed prior to consolidation.

Two replacement disks (58-1, -2) were subsequently consolidated. Metallographic analysis of the TIP tested fill tube indicated that both disks 58-1 and 58-2 were successfully consolidated containing $<0.1\%$ porosity associated with hollow particles (Figure 9).

The final set of disks were fabricated with tooling modifications to more closely form the disk shape to target sonic dimensions. The initial HIP consolidation, disk 76-1, was not successful due to container failure as evidenced by a TIP response as shown in Figure 10. This container failure was associated with the subsurface inclusions in the SAE 1008 material. A detailed discussion of container material quality is given in the container fabrication portion of Section 3. Another heat of material which met AMS 5041 specifications was used for the remaining containers. The final two disks, 80-1 and 80-2, were successfully consolidated showing $<0.1\%$ TIP response due to hollow particles as shown in Figure 11.

CONTAINER REMOVAL AND HEAT TREATMENT

The mild steel container of each consolidated disk was removed by acid pickling in a hot ($82^{\circ}\text{C}/130^{\circ}\text{F}$) HNO_3 - HCl acid solution prior to heat treatment. The composition of the acid solution is as follows:

- 160 ml HNO_3
- 820 ml HCl
- 0.3 ml wetting agent — ORVUS — WA by Procter & Gamble
- 34.8 grams/l Anhydrous FeCl_3

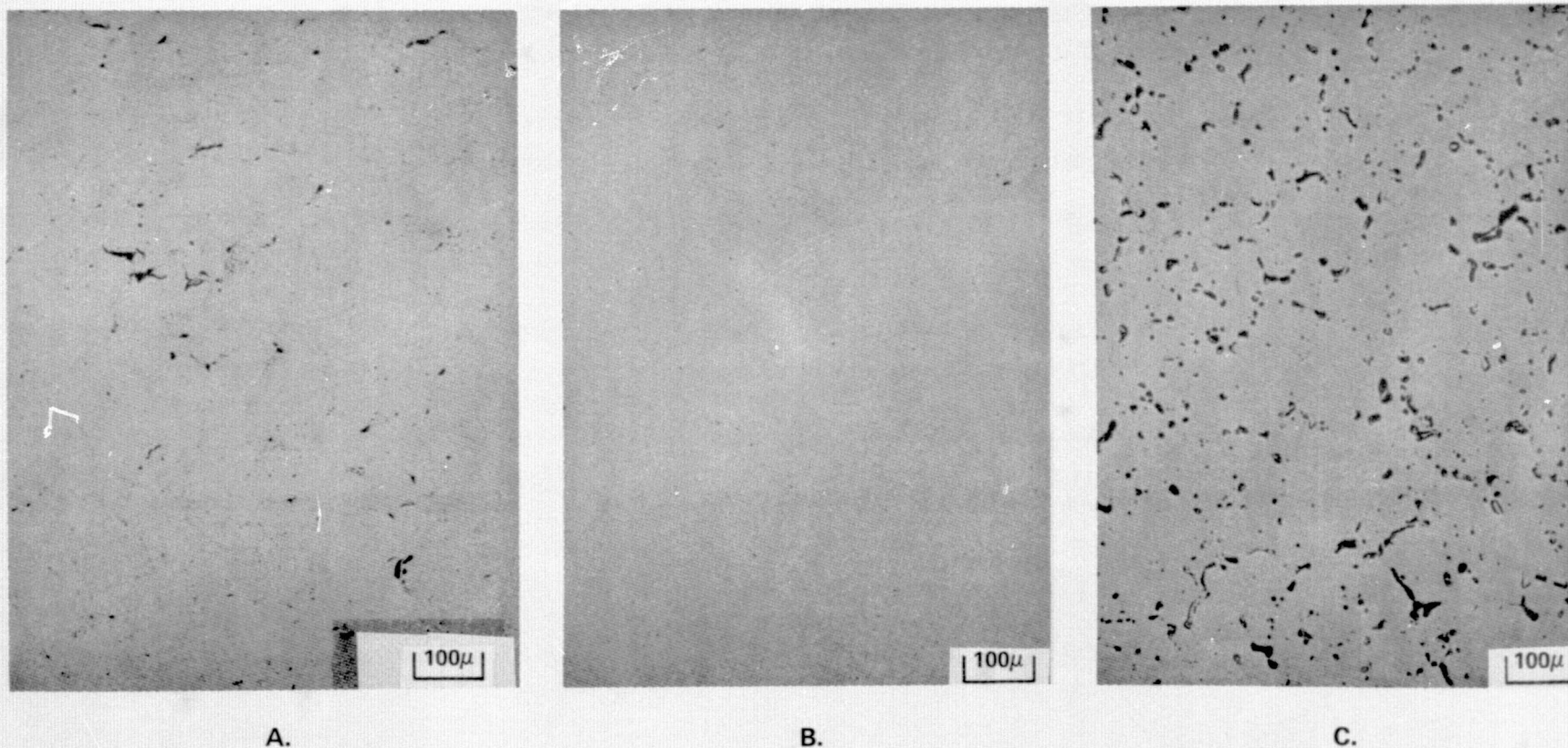
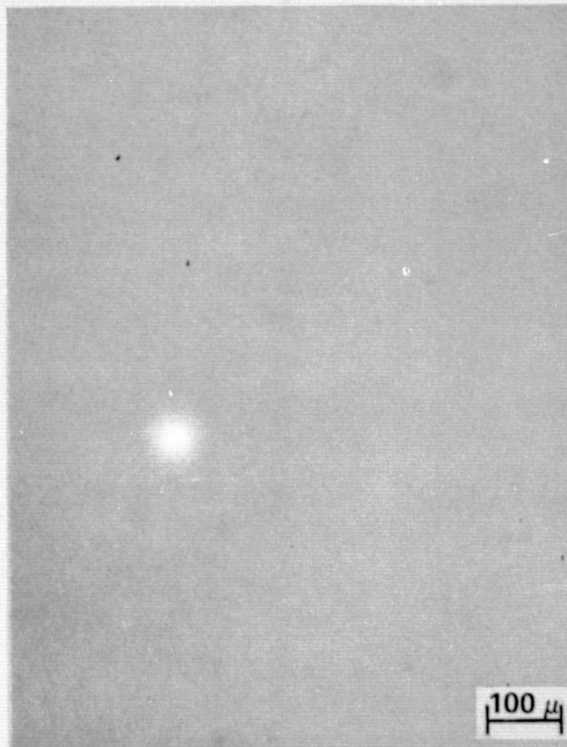


Figure 8 Microstructures of Specimens Taken from the Fill Tube of Disks 50-1 (Left), 50-2 (Center), and 50-3 (Right) and TIP Tested at 1204°C (2200°F)/4 hrs./AC. The microstructure of disks 50-1 and 50-3 displayed unacceptable porosity at prior particle boundaries (triple points) due to container failure prior to consolidation, while disk 50-2 microstructure indicated successful consolidation.

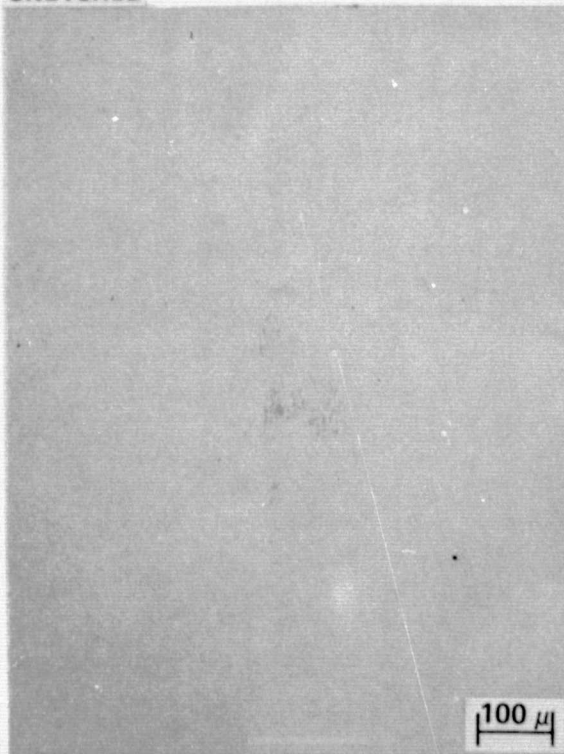
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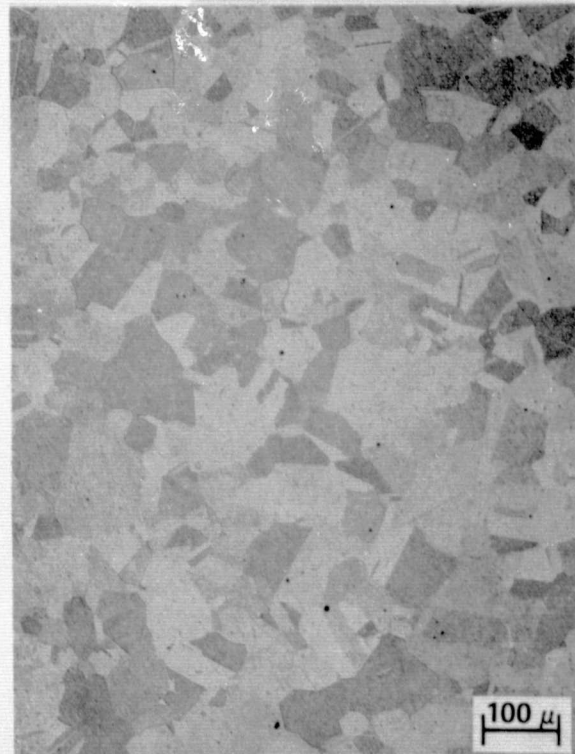
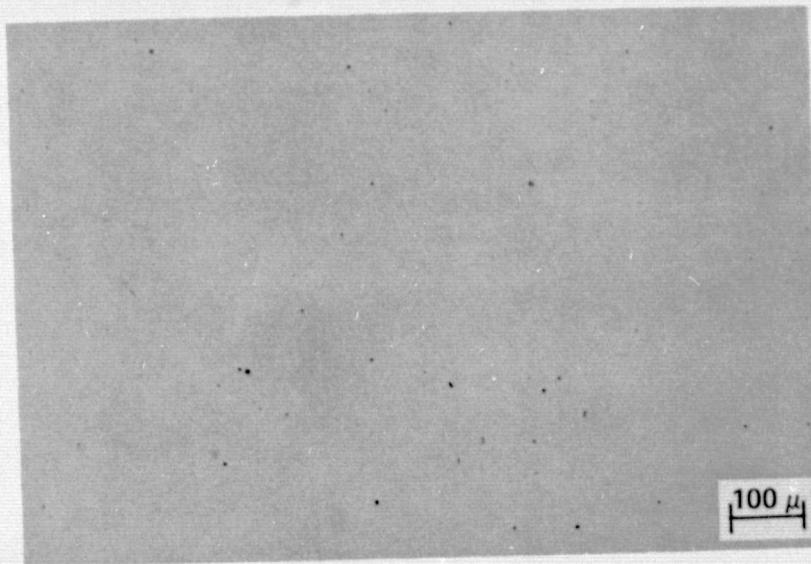


Figure 9 Microstructures of Specimens Taken From Disks 58-1 (Top) and 58-2 (Bottom) TIP Tested at 1204°C (2200°F)/4 hrs./AC Showing Acceptable Consolidations. TIP response (<0.1%) is associated with hollow particles.

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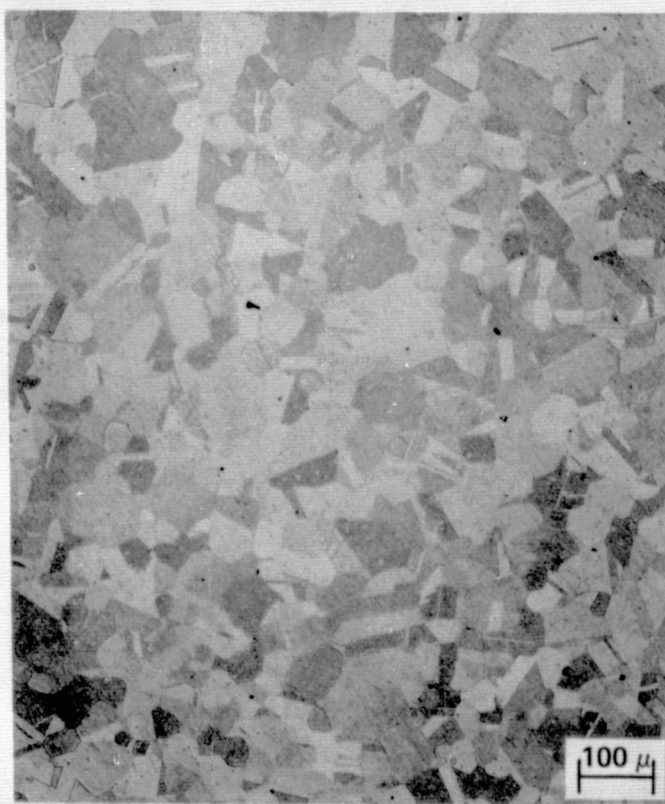
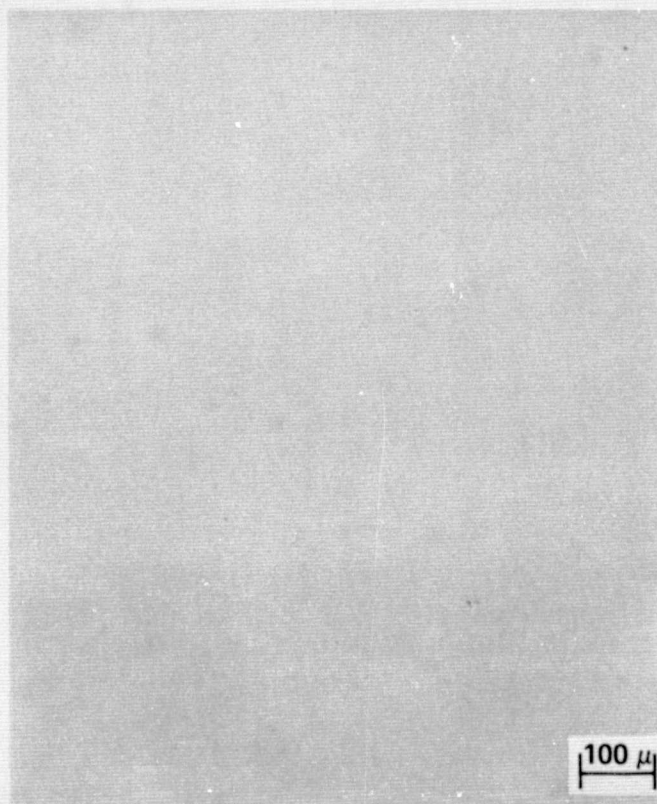
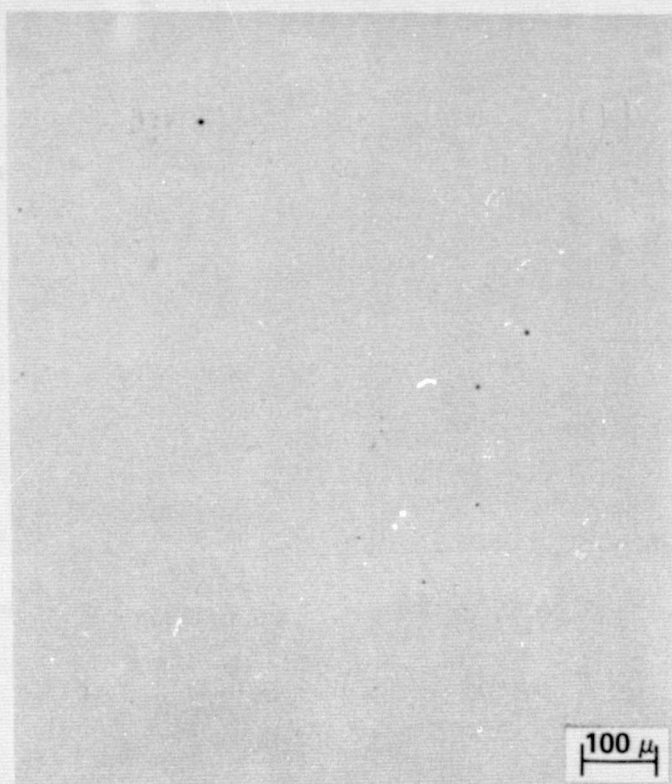


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Figure 10 Results of Thermally Induced Porosity Test [1204°C (2200°F)/4 hrs./AC] for Disk 76-1 Showing an Undesirable Amount of Fine Porosity Probably Related to Container Failure Prior to HIP Consolidation. Porosity such as that shown by arrows appears associated with powder particle triple points.

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Figure 11 Microstructures of Specimens Taken From Disks 80-1 (Top) and 80-2 (Bottom) TIP Tested at 1204°C (2200°F)/4 hrs./AC Showing Acceptable Consolidations.

The heat treatment selected for HIP low carbon Astroloy was based upon that used for conventionally forged Astroloy. Each disk was heat treated at 1116°C (2040°F)/2 hrs / AC + 871°C (1600°F)/8 hrs/AC + 980°C (1800°F)/4 hrs/AC + 649°C (1200°F)/24 hrs/AC + 760°C (1400°F)/8 hrs/AC. The initial group of three disks (50-1, -2, -3) was solution heat treated in a salt bath media while the remaining group (58-1, -2, 76-1, 80-1, -2) was heat treated in an air electric furnace.

DIMENSIONAL ANALYSIS

Dimensional data were determined utilizing a high accuracy, automated mechanical measuring system in conjunction with an automated computer system for recording data on paper tape. The data collected were transmitted to a second computer containing a program to analyze the dimensional data.

A vertical probe with three degrees of freedom (x, y, z motion) was manually placed on the disk as shown in Figure 12. Forty three (43) scans, obtaining dimensional measurements at approximately every inch on the circumference (6° increment on the rim to 30° on the bore), yielded over 1800 data points which were recorded as shown in Figure 13. One face of the disk was measured in a single session and the disk was inverted to measure the opposite face. A reference plane was established by identifying three points, 120° apart, on the outer diameter of the disk with a SiC tipped clamp bolt so that this same reference plane could be established when the disk was inverted.

All disks were dimensionally measured in the fully heat treated condition with the container removed. For the first set of disks (50-1, -2, -3) that was dimensionally analyzed, the reference plane was not retained accurately when the disk was inverted. These disks were also measured by conventional mechanical methods. The actual dimension measured and the corresponding target dimensions are shown in Table VIII. The data for disks 50-1 and 50-3 do not allow a valid assessment of dimensional accuracy as these disks were not completely consolidated because of container leakage.

Two additional disks (58-1, -2) were consolidated as replacements for disk 50-1 and 50-3 to complete the first set. These replacement disks had the target dimensions shown previously in Table VI. Disk 58-1 was analyzed in detail in order to supply a basis for modifying the tooling for the final set of two disks (80-1, 80-2). The minimum and maximum dimensional deviation from target of each face for disk 58-1 are presented in Figure 14.

Based on an analysis of the minimum deviation from target value of each face, the tooling was modified as required to approach target net sonic shape. For example, the rear web face was modified -0.203cm (0.080 in.) because disk 58-1 was at least 0.208 cm (0.082 in.) oversize as shown in Figure 14. However, for faces which exhibited significant scatter, the dimensions were modified based on best judgment. For example the rim diameter, which showed a minimum/maximum deviation of +.106cm (.040 in.)/-.342cm (.135 in.) was modified by .203cm (.080 in.). A comparison of the dimensional deviations from target values for disks 58-1, 80-1, and 80-2 along with the dimensional change of the tooling, are given in Figure 14. These results showed disks 80-1 and 80-2 generally responded to the dimensional modifications to achieve as-HIP'ed surfaces closer to target dimensions. Approximately 90% of the disk-shape surfaces responded satisfactorily to the dimensional modifications. A few of the surfaces (e.g., front and rear web face) defining the disk thickness did not respond well to the dimensional modification.



Figure 12 High Accuracy, Automated Mechanical Measuring System

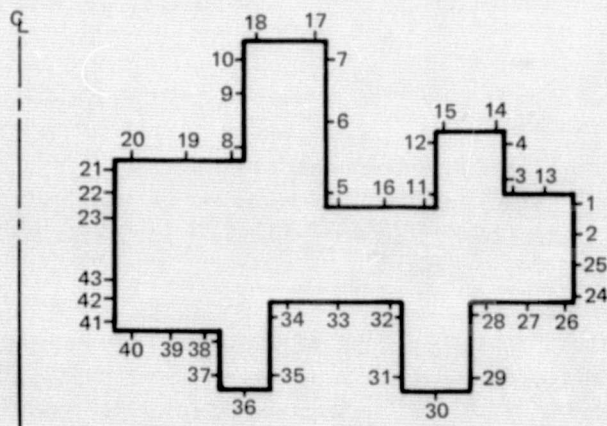
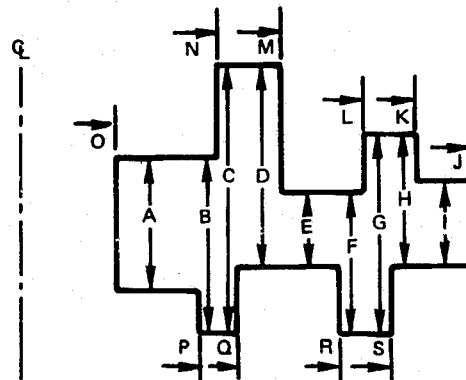


Figure 13 Schematic of Radial Section of Disk Showing Scan Locations

TABLE VIII
DIMENSIONAL ANALYSIS OF
DISK 50-1

Dimension	Target		Minimum Dimensions		Minimum Deviation		Maximum Dimensions		Maximum Deviation	
	(in.)	(cm)	(in.)	(cm)	(in.)	(cm)	(in.)	(cm)	(in.)	(cm)
A	3.12	7.92	3.33	8.46	0.21	0.53	3.40	8.64	0.28	0.71
B	4.06	10.31	4.26	10.82	0.20	0.51	4.35	11.05	0.29	0.74
C	6.09	15.47	6.26	15.90	0.17	0.43	6.40	16.26	0.31	0.79
D	4.59	11.66	4.74	12.04	0.15	0.38	4.89	12.42	0.30	0.76
E	1.84	4.67	1.86	4.72	0.02	0.05	2.11	5.36	0.27	0.69
F	3.34	8.48	3.35	8.51	0.01	0.03	3.61	9.17	0.27	0.69
G	4.53	11.51	4.60	11.68	0.07	0.18	4.82	12.24	0.29	0.74
H	3.03	7.70	3.03	7.70	0.00	0.00	3.28	8.33	0.25	0.64
I	2.15	5.46	2.04	5.18	-0.11	0.28	2.21	5.61	0.06	0.15
J	9.80	24.89	9.77	24.82	-0.03	-0.08	9.96	25.30	0.16	0.41
K	9.58	24.33	8.62	21.89	0.04	0.10	8.84	22.45	0.26	0.66
L	7.27	18.47	7.32	18.59	-0.05	-0.13	7.13	18.11	0.14	0.36
M	5.72	14.53	5.72	14.53	0.00	0.00	5.95	15.11	0.23	0.58
N	4.10	10.41	4.15	10.54	-0.05	-0.13	3.95	10.03	0.15	0.38
O	1.86	4.72	1.88	4.78	-0.02	-0.05	1.72	4.37	0.14	0.36
P	3.74	9.50	3.82	9.70	-0.12	-0.30	3.74	9.50	0.00	0.00
Q	4.84	12.29	4.85	12.32	0.01	0.03	4.95	12.57	0.11	0.28
R	6.76	17.17	6.77	17.20	-0.01	-0.03	6.68	16.97	0.08	0.20
S	8.10	20.57	8.37	21.26	0.27	0.69	8.50	21.59	0.40	1.02



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TABLE VIII (Cont'd)
DIMENSIONAL ANALYSIS OF
DISK 50-2

Dimension	Target		Minimum Dimensions		Minimum Deviation		Mechanically Measured Dimensions Maximum Dimensions		Maximum Deviation	
	(in.)	(cm)	(in.)	(cm)	(in.)	(cm)	(in.)	(cm)	(in.)	(cm)
A	2.92	7.42	3.13	7.95	0.21	0.53	3.18	8.08	0.26	0.66
B	3.86	9.80	4.06	10.31	0.20	0.51	4.17	10.59	0.31	0.79
C	5.80	14.73	5.99	15.21	0.19	0.48	6.13	15.57	0.33	0.84
D	4.30	10.92	4.49	11.40	0.19	0.48	4.64	11.79	0.34	0.86
E	1.63	4.14	1.70	4.32	0.07	0.18	1.92	4.88	0.29	0.74
F	3.13	7.95	3.15	8.00	0.02	0.05	3.36	8.53	0.23	0.58
G	4.37	11.10	4.44	11.28	0.07	0.18	4.70	11.94	0.33	0.84
H	2.87	7.29	2.93	7.44	0.06	0.15	3.11	7.90	0.24	0.61
I	1.87	4.75	1.87	4.75	0.00	0.00	2.02	5.13	0.15	0.38
J	9.64	24.49	9.60	24.38	-0.04	0.10	9.72	24.69	0.12	0.30
K	8.45	21.46	8.50	21.59	0.05	0.13	8.61	21.87	0.16	0.41
L	7.27	18.47	7.26	18.44	0.01	0.03	7.16	18.19	0.11	0.28
M	5.56	14.12	5.64	14.33	0.08	0.20	5.74	14.58	0.18	0.46
N	4.10	10.41	4.07	10.34	0.03	0.08	3.99	10.13	0.11	0.28
O	1.98	5.03	1.99	5.05	-0.01	-0.03	1.90	4.83	0.08	0.20
P	3.78	9.60	3.79	9.63	-0.01	-0.03	3.71	9.42	0.07	0.18
Q	4.67	11.86	4.75	12.06	0.08	0.20	4.85	12.32	0.18	0.46
R	6.76	17.17	6.71	17.04	0.05	0.13	6.65	16.89	0.11	0.28
S	7.93	20.14	7.95	20.19	0.02	0.05	8.06	20.47	0.13	0.33

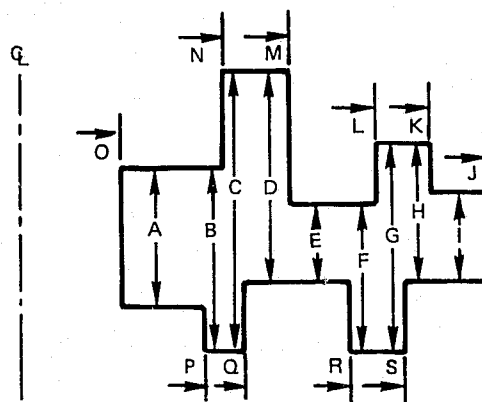
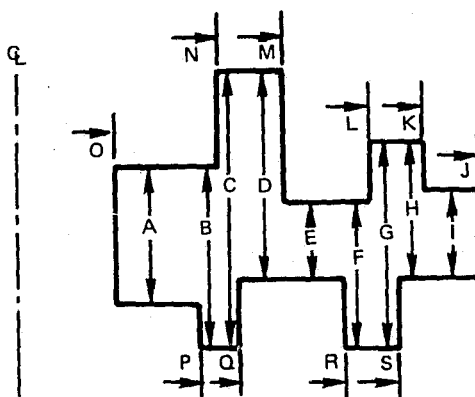


TABLE VIII (Cont'd)

**DIMENSIONAL ANALYSIS OF
DISK 50-3**

Dimension	Mechanically Measured Dimensions									
	Target		Minimum Dimensions		Minimum Deviation		Maximum Dimensions		Maximum Deviation	
	(in.)	(cm)	(in.)	(cm)	(in.)	(cm)	(in.)	(cm)	(in.)	(cm)
A	2.79	7.09	3.12	7.92	0.33	0.84	3.16	8.03	0.37	0.94
B	3.78	9.60	4.14	10.52	0.36	0.91	4.17	10.59	0.39	0.99
C	5.72	14.53	6.01	15.27	0.29	0.74	6.11	15.52	0.39	0.99
D	4.22	10.72	4.54	11.53	0.32	0.81	4.58	11.63	0.36	0.91
E	1.55	3.94	1.75	4.44	0.20	0.51	1.82	4.62	0.27	0.69
F	2.53	6.43	2.64	6.71	0.11	0.28	2.74	6.96	0.21	0.53
G	3.77	9.58	3.91	9.93	0.14	0.25	4.02	10.21	0.25	0.64
H	2.78	7.06	2.88	7.32	0.10	0.25	3.00	7.62	0.22	0.56
I	1.77	4.50	1.82	4.62	0.05	0.13	1.89	4.80	0.12	0.30
J	9.60	24.38	9.58	24.33	-0.02	0.05	9.68	24.59	0.08	0.20
K	8.40	21.33	8.50	21.59	0.10	0.25	8.59	21.82	0.19	0.48
L	7.34	18.64	7.32	18.59	0.02	0.05	7.23	18.36	0.11	0.28
M	5.52	14.02	5.63	14.30	0.11	0.28	5.70	14.48	0.18	0.46
N	4.17	10.60	4.14	10.52	0.03	0.08	4.09	10.39	0.08	0.20
O	2.02	5.13	2.03	5.16	-0.01	0.03	1.97	5.00	0.05	0.13
P	3.88	9.86	3.87	9.83	0.01	0.03	3.84	9.75	0.04	0.10
Q	4.62	11.73	4.73	12.01	0.11	0.28	4.77	12.12	0.15	0.38
R	6.78	17.22	6.78	17.22	0.00	0.00	6.71	17.04	0.07	0.18
S	7.88	20.02	7.99	20.29	0.11	0.28	8.03	20.40	0.15	0.38



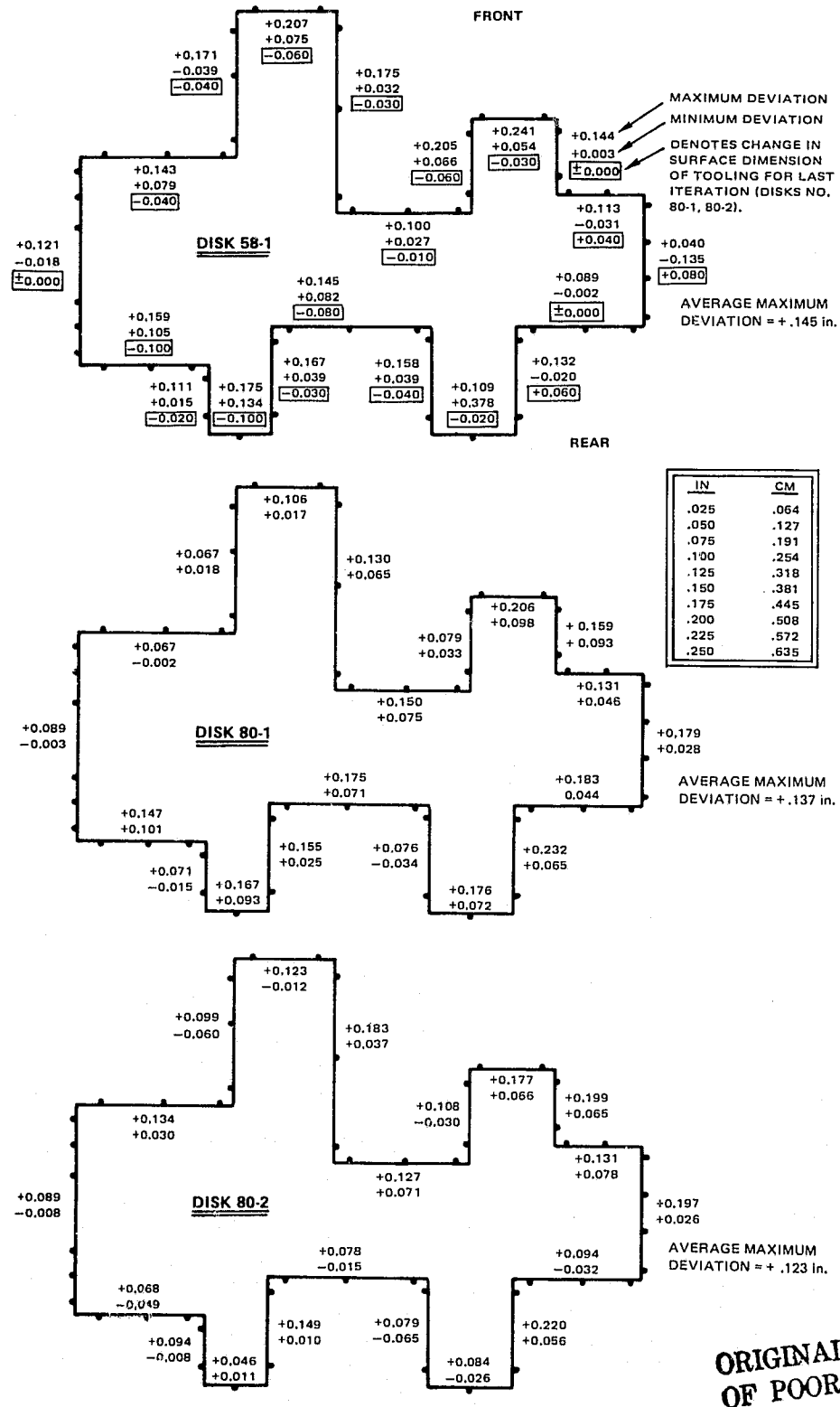


Figure 14 Dimensional Analysis of Disks 58-1, 80-1, and 80-2 Showing Minimum/Maximum Deviations From Target Dimensions. Approximately 90% of the surfaces of disks 80-1 and 80-2 responded to the dimensional modifications incorporated relative to disk 58-1. Primary dimensions are given in inches. A metric conversion table is given.

The average deviation for each scan was calculated and presented in Figure 15. The average deviation from target dimension was reduced from 0.220 cm (.087 in) for disk 58-1 to 0.213 cm (0.084 in.) and 0.167 cm (.066 in.) for disk 80-1 and 80-2, respectively (Figure 15). Approximately 90% of the surfaces responded to the dimensional modification.

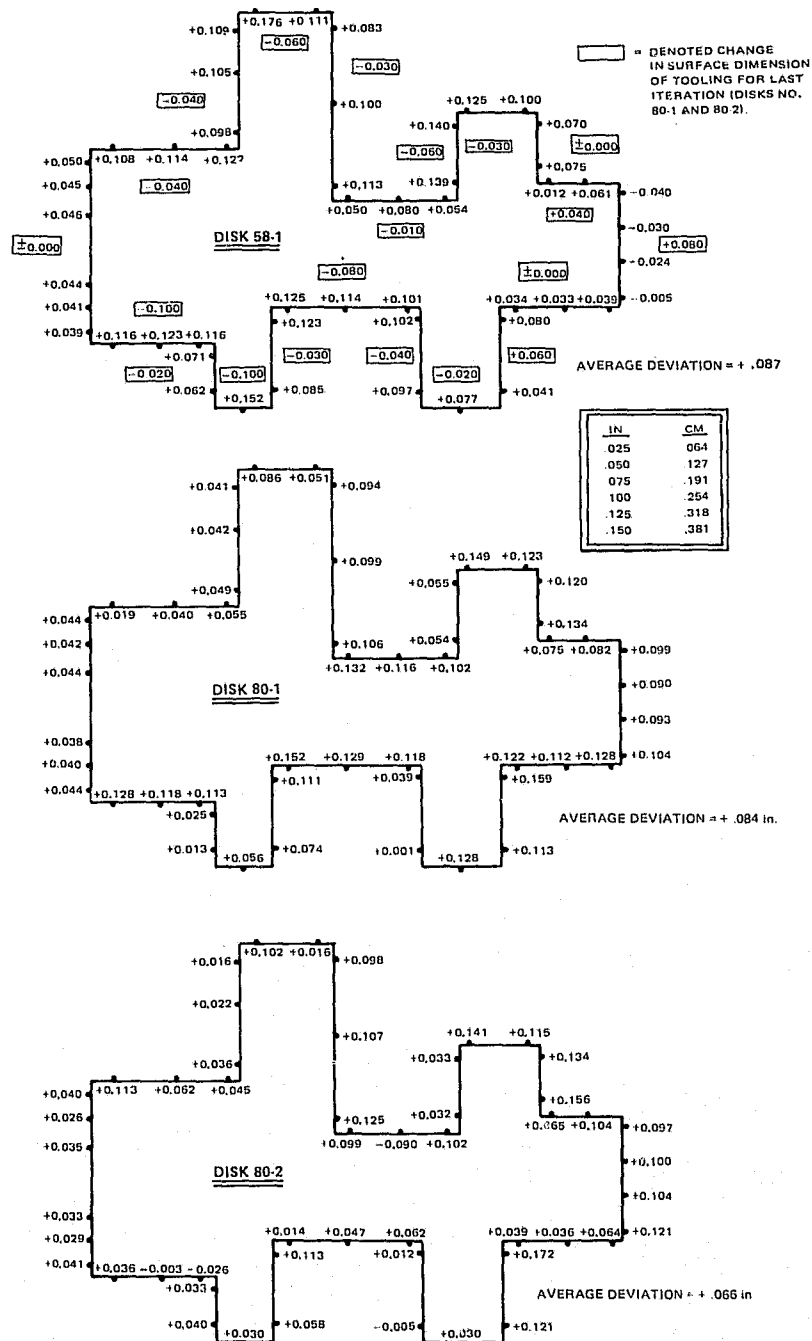


Figure 15 Dimensional Analysis of Disks 58-1, 80-1 and 80-2 Showing the Average Deviation From Target Dimensions For Each Scan. Approximately 90% of the surfaces of disks 80-1 and 80-2 responded to the dimensional modifications incorporated relative to disk 58-1. Primary dimensions are given in inches. A metric conversion table is given.

ULTRASONIC INSPECTION

Ultrasonic inspection was conducted to determine the quality of consolidation by utilizing the following components:

- Branson 303 Pulser/Reducer
- 1.27 cm (0.5 in.), 10 MHz focused transducer for 0.254 cm (0.1 in.) to 2.54 cm (1.00 in.) metal travel (3.81 cm/1.5 in. water travel)
- 1.91cm (.75 in.), 5 MHz focused transducer for 2.54cm (1.0 in.) to 10.16cm (4.0 in.) metal travel (7.62 cm/3.0 in. water travel)
- No. 1 flat-bottom-hole-machined test blocks

The initial set of three disks (50-1, -2, -3) which had been heat treated in a salt bath media was grit blasted using #120 grit aluminum oxide to remove the scale prior to ultrasonic inspection. Inspection of these three disks was conducted utilizing a No. 1 flat-bottom-hole (1/64") machined test block standard and other than a crack visible in 50-1, no rejectable indications were detected. Disk 50-2 was then machined to blueprint sonic configuration and reinspected to a No. 1 flat-bottom-hole. Again, no rejectable indications were found.

The remaining disks (58-1, 58-2, 80-1, 80-2) were inspected to a No. 1 flat-bottom-hole (1/64") in the as-HIP + decanned and heat treated condition without grit blasting and were found to be defect free.

For both conventionally forged and HIP nickel-base alloys, an uninspectable area exists within approximately .254 cm (0.100 inch) of the surface. The front and rear surface resolution for the as grit blasted surface (disks 50-1, 50-2, 50-3) and as heat treated surface (58-1, 58-2, 80-1, 80-2) was similar, while only slightly better for the machined surface (disk 50-2). Current ultrasonic inspection technology for conventionally forged Waspaloy ® has a resolution sensitivity equal to a No. 1 machined flat-bottom hole .13 cm (3/64 inch) because of the relatively large grain size. However, the fine grain, homogenous HIP microstructure improved the ultrasonic sensitivity enabling resolution of a defect equivalent to a machined No. 1 flat-bottom hole .056 cm (1/64 inch) in diameter. For these reasons, HIP sonic disk shapes with an as heat treated surface can be successfully inspected with a greater sensitivity than conventionally forged Waspaloy ® machined to sonic shape.

MECHANICAL PROPERTIES OF INTEGRAL TEST COUPON RING

Tensile and stress rupture testing of specimens taken from a location adjacent to the finished part is a routine product acceptance procedure in the production of current Waspaloy disk forgings. To conduct a similar product acceptance test on the HIP Astroloy consolidations, test specimens were machined from the integral test coupon ring located adjacent to the rear outer seal land. A description of each specimen type is given in "Test Specimens and Procedures", Section 5. Standard ASTM procedures were used for tensile, stress-rupture and creep testing except for the initial creep test for disk 50-2 as discussed later.

Tensile, stress-rupture and creep properties of all consolidated disks (50-2, 58-1, 80-1 and 80-2) exceeded target requirements except for time to 0.1% creep for disk 50-2 as shown in

Tables IX-XI. The inaccurate creep value is attributable to incorrect procedures employed for measuring primary creep. This inaccuracy was resolved for subsequent creep tests. Additional material was unavailable for retest.

Microexamination of failed specimens revealed an intergranular mode of failure for room temperature and 1000°F tensile as well as 1350°F stress-rupture tests. Photomicrographs of intergranular failure typical for both tensile and stress-rupture tests are shown in Figure 16.

TABLE IX
TENSILE PROPERTIES FROM
INTEGRAL TEST COUPON RINGS

Disk No.	Test Temperature	UTS MPa (ksi)	0.2% Y.S. MPa (ksi)	%EL	%RA
50-2	RT ↓	1372 (199)	949 (138)	23.7	26.3
58-1		1372 (199)	965 (140)	23.3	26.6
		1366 (201)	986 (143)	23.1	25.2
58-2		1382 (200)	972 (141)	23.2	27.5
		1382 (200)	972 (141)	23.2	27.2
80-1		1368 (198)	931 (135)	23.2	30.1
80-1		1371 (199)	932 (135)	24.2	32.5
80-2		1372 (199)	944 (137)	23.5	32.2
80-2		1383 (201)	960 (139)	23.0	32.6
Target min.		1241 (180)	862 (125)	15.0	18.0
50-2	538°C (1000°F) ↓	1265 (184)	900 (131)	17.0	23.1
		1259 (183)	883 (128)	19.4	20.6
58-1		1255 (182)	889 (129)	23.2	22.5
		1282 (186)	1282 (132)	21.5	23.1
58-2		1269 (184)	910 (132)	21.2	24.2
		1255 (182)	938 (136)	21.2	23.1
80-1		1262 (183)	866 (126)	21.2	25.2
80-1		1280 (186)	870 (126)	21.8	29.6
80-2		1277 (185)	872 (127)	21.8	29.1
80-2		1287 (186)	864 (125)	22.5	27.9
Target min.		1103 (160)	758 (110)	15.0	18.0

TABLE X
STRESS RUPTURE OF INTEGRAL TEST COUPON RINGS

732°C (1350°F)/552 MPa (80 ksi)

Disk No.	Time to Failure - hours	% EL	% RA	Failure Location
50-2	310	15.5	25.0	Smooth
	382	12.2	23.4	Smooth
58-1	268	15.6	24.3	Smooth
58-1	219	15.1	24.5	Smooth
58-2	177	10.3	23.6	Smooth
58-2	335	19.8	22.3	Smooth
80-1	291	16.5	21.2	Smooth
80-1	301	18.5	23.1	Smooth
80-2	299	17.8	22.3	Smooth
80-2	281	17.4	21.4	Smooth
Target min.	23	8.0		Smooth

TABLE XI
CREEP PROPERTIES OF INTEGRAL TEST COUPON RINGS

704°C (1300°F)/510 MPa (74 ksi)

Disk No.	Time to 0.1% Elongation - hours	Time to 0.2% Elongation - hours
50-2	*	*
58-1	194	341
58-2	207	366
80-1	200	353
80-2	234	378
Target min.	100	

[*Primary creep not accurately measured.]

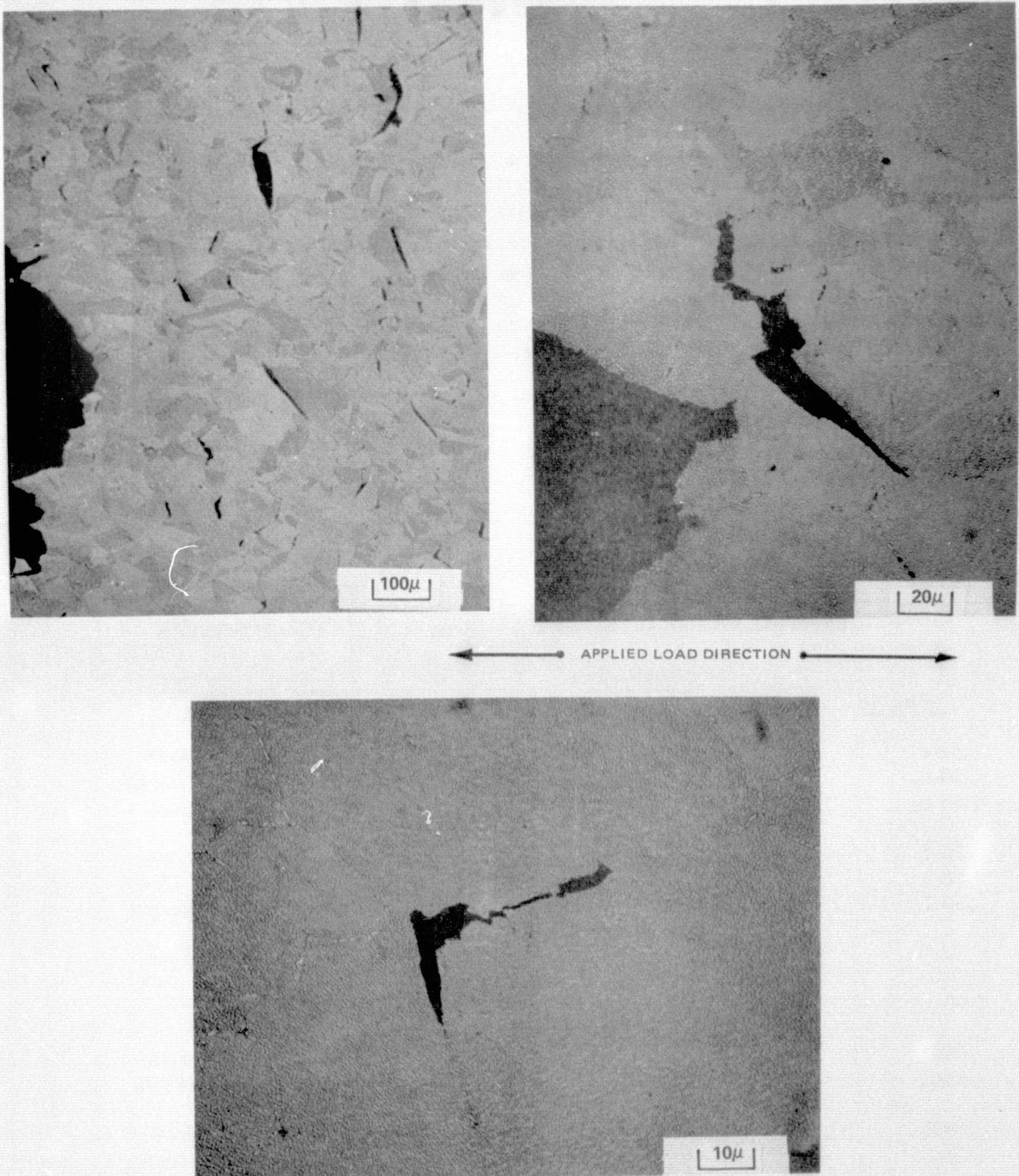


Figure 16 Photomicrographs of Failed Stress-Rupture Specimens Taken From Disk 80-1 and Tested at 732°C (1350°F)/552 MPa (80 ksi) for 291 Hours Showing an Intergranular Mode of Failure. Intergranular mode of failure was also observed for room temperature and 538°C (1000°F) tensile tests.

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INTERSTITIAL GAS ANALYSIS

Interstitial gas analyses, using both vacuum fusion and inert gas fusion analysis techniques, were performed on samples taken for integral test rings of disks 50-1, 50-2, 50-3, 58-1, 58-2, 80-1 and 80-2. Results are given in Table XII. While nitrogen target minimum was met, the reported oxygen content varied with some results over target value. The values determined by vacuum fusion analysis were generally lower than those determined by inert gas fusion analysis. A review of the techniques revealed that the vacuum fusion technique generally utilizes a lower melt temperature range than that for the inert gas fusion technique. This lower melting range could have resulted in incomplete extraction of gas, thereby yielding lower than actual oxygen content. A more detailed discussion on interstitial gas analysis is given in "Disk Characterization", Section 5.

PROCESS CONTROL & ACCEPTANCE CRITERIA

A process control plan and Acceptance Criteria reflecting the results of Task I is presented in Appendix A and B, respectively.

TABLE XII

INTERSTITIAL GAS ANALYSIS OF INTEGRAL TEST COUPON SPECIMENS

<u>Disk No.</u>	<u>O</u>	<u>Gas Analysis</u>	<u>N</u>	<u>Analysis Technique and Source</u>
50-1	66 ppm		34 ppm	Vacuum Fusion – P&WA
50-1	117		24	Inert Gas Fusion – P&WA
50-1	69		28	Inert Gas Fusion – Udimet
50-2	67		28	Vacuum Fusion – P&WA
50-2	107		21	Inert Gas Fusion – P&WA
50-2	110		30	Inert Gas Fusion – Udimet
50-3	65		34	Vacuum Fusion – P&WA
50-3	100		23	Inert Gas Fusion – P&WA
50-3	82		19	Inert Gas Fusion – Udimet
58-1	96		19	Vacuum Fusion – P&WA
58-1	122		26	Inert Gas Fusion – P&WA
58-2	81		23	Vacuum Fusion – P&WA
58-2	120		23	Inert Gas Fusion – P&WA
80-1	124		16	Inert Gas Fusion – P&WA
80-2	116		18	Inert Gas Fusion – P&WA
Target	< 100 ppm		< 50 ppm	

4.0 TASK II -- DISK MANUFACTURE

MACHINABILITY

Lathe turning, milling, drilling and reaming, and broaching operations were performed on specimens taken from 12.7cm (5 in.) diameter x 12.7cm (5 in.) diameter consolidations that were HIP[1213°(2215°F)/103MPa(15KSI)/3 hrs] and heat treated [1116°C(2040°F)/2 hrs/AC + 871°C(1600°F)/8 hrs/AC + 980°C(1800°F)/4 hrs/AC + 649°C(1200°F)/24 hrs/AC + 760°C(1400°F)/8 hrs/AC] by P&WA - Materials Engineering Research Laboratory. Standard conventional tools were used and machining parameters for conventionally forged Waspaloy® were selected for these trials. A listing of the parameters and specimens utilized in these machinability tests are shown in Tables XIII and Figure 17, respectively. Machinability was based on visual observation of the chipping characteristics and amount of chip removed. These tests showed that the machinability of direct HIP low carbon Astroloy was similar to that of conventionally forged Waspaloy®.

TABLE XIII

PARAMETERS USED FOR MACHINABILITY TESTS

Lathe Turning - Roughing

Cutting tool material	— Sintered tungsten carbide
Speed	— 21.3m/min (70 SFPM)
Feed	— .03cm (.011 in)/Revolution
Depth	— .254 cm (.100 in)/Side
Tool Geometry	— Positive back and side rake, 10° lead angle, .119 cm (.047 in) nose radius
Coolant	— Water-emulsified compound

Lathe Turning - Finishing

Cutting tool material	— Sintered tungsten carbide
Speed	— 39 meters/min (130 SFPM)
Feed	— .013 cm (.005 in)/Rev.
Depth	— .051 cm (.020 in)/Side
Tool Geometry	— Positive back and side rake, 10° lead angle, .119 cm (.047 in) nose radius
Coolant	— Water emulsified compound

Milling

Cutting tool material	— AISI M-42
Speed	— 7.8 meters/min (26 SFPM)
Feed	— 1.43 cm (.562 in)/min
Depth	— .254 cm (.100 in)
Coolant	— Water-emulsified compound

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TABLE XIII (Cont'd)

Drilling

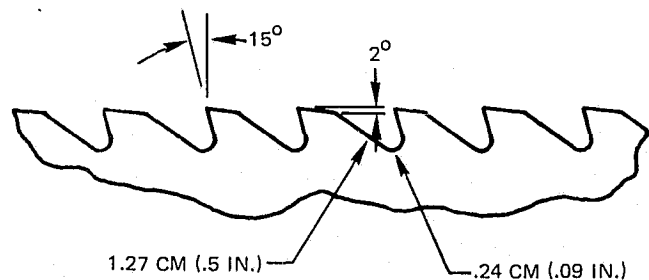
Cutting tool material	— AISI M-42
Hole size	— .95 cm (.375 in)
R.P.M.	— 202
Feed	— 1.59 cm (.625 in)/min
Tool Geometry	— 135° Including angle with # 33 point
Coolant	— Water-emulsified compound

Reaming

Cutting tool material	— Tungsten carbide
Material removed	— .013cm (.005) on diameter
Spindle speed RPM	— 136
Feed	— 2.2 cm (0.875 in.)/min
Finish	— .76 micrometer (30 A-A)
Tool Geometry	— Solid carbide .97 cm (.380 in.) dia. with .08 cm (.031 in.) x 45° chamfer
Coolant	— Water-emulsified compound

Broaching

Tool cutting material	— (AISI T-15)
Speed	— 3.3 meter/min (11 SFPM)
Coolant	— High viscosity cutting oil (SUS 100)
Surface Finish	— .17 micrometer (9 A-A)
Tool Geometry (shown below)	—



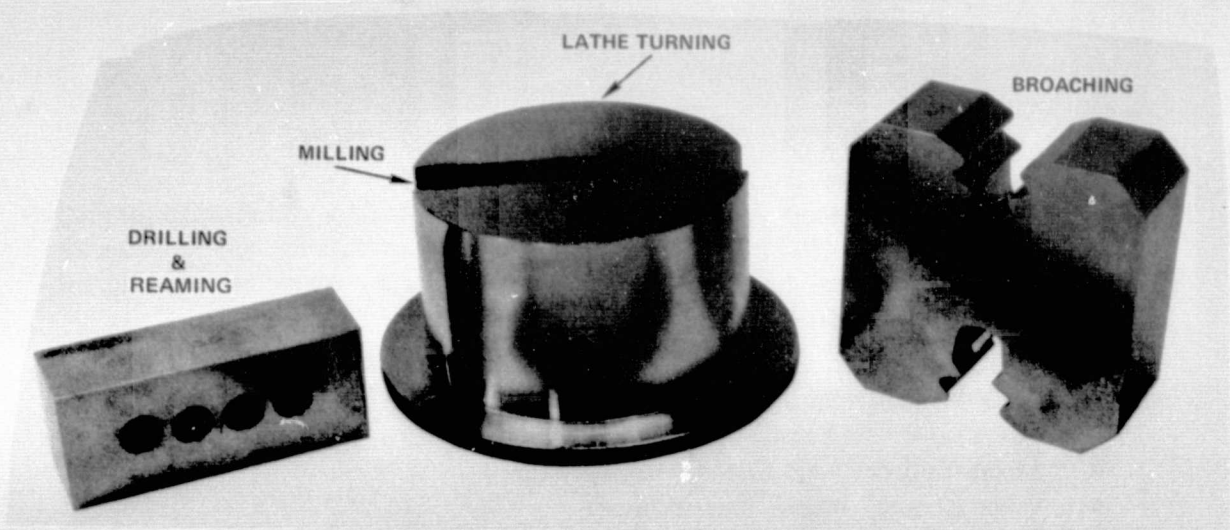


Figure 17 Machinability Tests of LC Astroloy

DISK MANUFACTURE

Disk 50-2 was selected for component machining of a JT8D first stage turbine disk (P/N 767601). Conventional machining techniques were utilized by a Pratt & Whitney Aircraft approved vendor. Dimensional analysis determined that the finish-machined disk conformed to blueprint requirements. The disk (Figure 18) was assigned the serial number G24302.

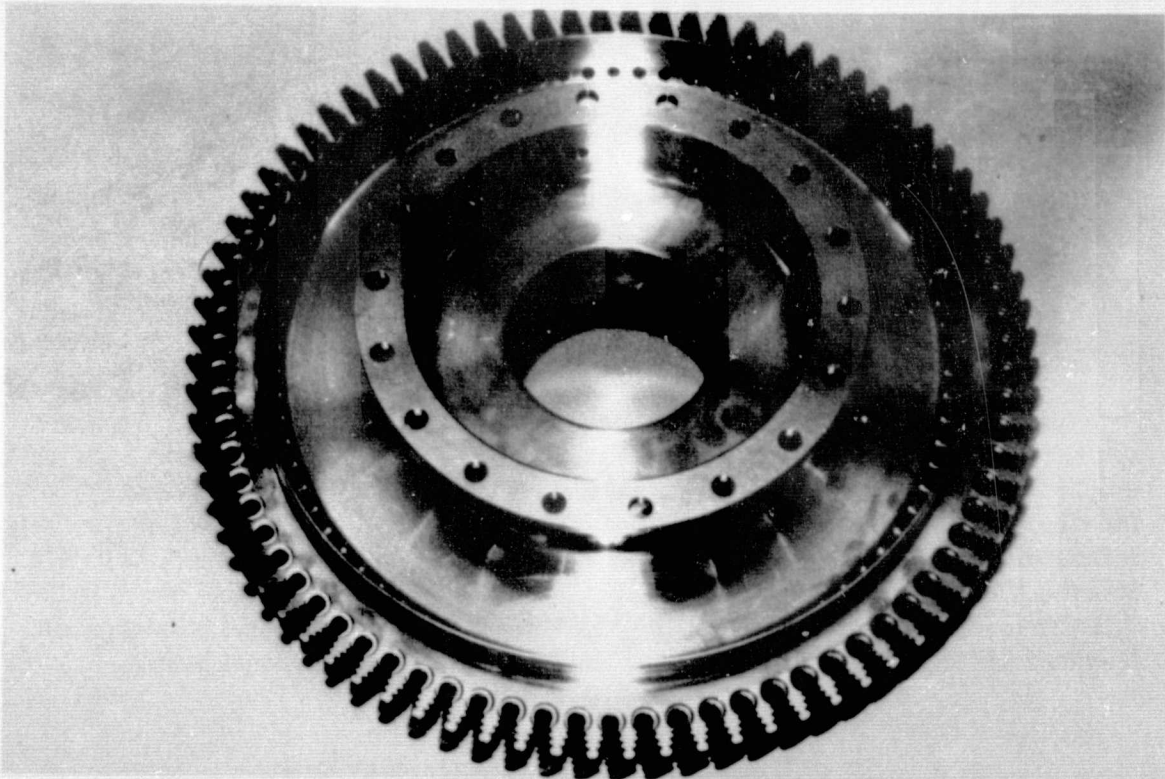


Figure 18 JT8D-17 First Stage Turbine Disk (P/N 767601, S/N G24302) Machined From HIP Consolidation 50-2.

5.0 TASK III – DISK CHARACTERIZATION

The purpose of this task was to characterize the structure, chemistry and mechanical properties of two of the five HIP disks produced in Task I and provide data for comparison with previous Pratt & Whitney Aircraft data to ensure that the material would meet engine disk design requirements. Mechanical properties tests performed were as follows:

- Ambient Temperature Tensile – 12 specimens
- 538°C(1000°F) Tensile – 12 specimens
- Stress-rupture (2 conditions) – 16 specimens
- Creep (2 conditions) – 16 specimens
- Fatigue Crack Propagation (2 conditions) – 8 specimens
- Notched Low Cycle Fatigue (3 conditions) – 24 specimens

Microstructural survey included replica electron microscopy of thick (bore, web) and thin (rim, flanges) sections after each heat treatment step.

Due to the discrepancy in reported interstitial gas content observed in Task I (See “Interstitial Gas Analysis”, Sec. 3), a round-robin analysis was performed in Task III. Additional gas analysis was performed to evaluate the existence of gradients from the HIP surface.

Chemical analysis was performed on each disk.

MECHANICAL PROPERTIES

Test Specimens and Procedures

Tensile, stress-rupture, creep, low-cycle fatigue and fatigue crack growth specimens were machined with tangential and radial orientations from various locations (i.e. rim, web, bore) of disks 58-1 and 80-1. The location with corresponding identity of each test specimen is indicated in Figure 19.

Smooth-bar tensile specimens (Figure 20) were removed from the bore, web, and rim of the disks and tested at room temperature and 538°C (1000°F). Combination smooth and notched bar stress-rupture specimens (Figure 21) were removed from the bore and rim in the tangential direction while creep-rupture specimens (Figure 22) were removed from web-radial and rim-tangential locations of the disk. Test conditions were 732°C (1350°F)/621 MPa (90 KSI) and 760°C (1400°F)/552 MPa (80 KSI) for stress-rupture and 649°C (1200°F)/758 MPa (110 KSI) and 704°C (1300°F)/552 MPa (80 KSI) for creep to 0.2% elongation. Standard ASTM procedures were used for tensile, stress-rupture, and creep testing.

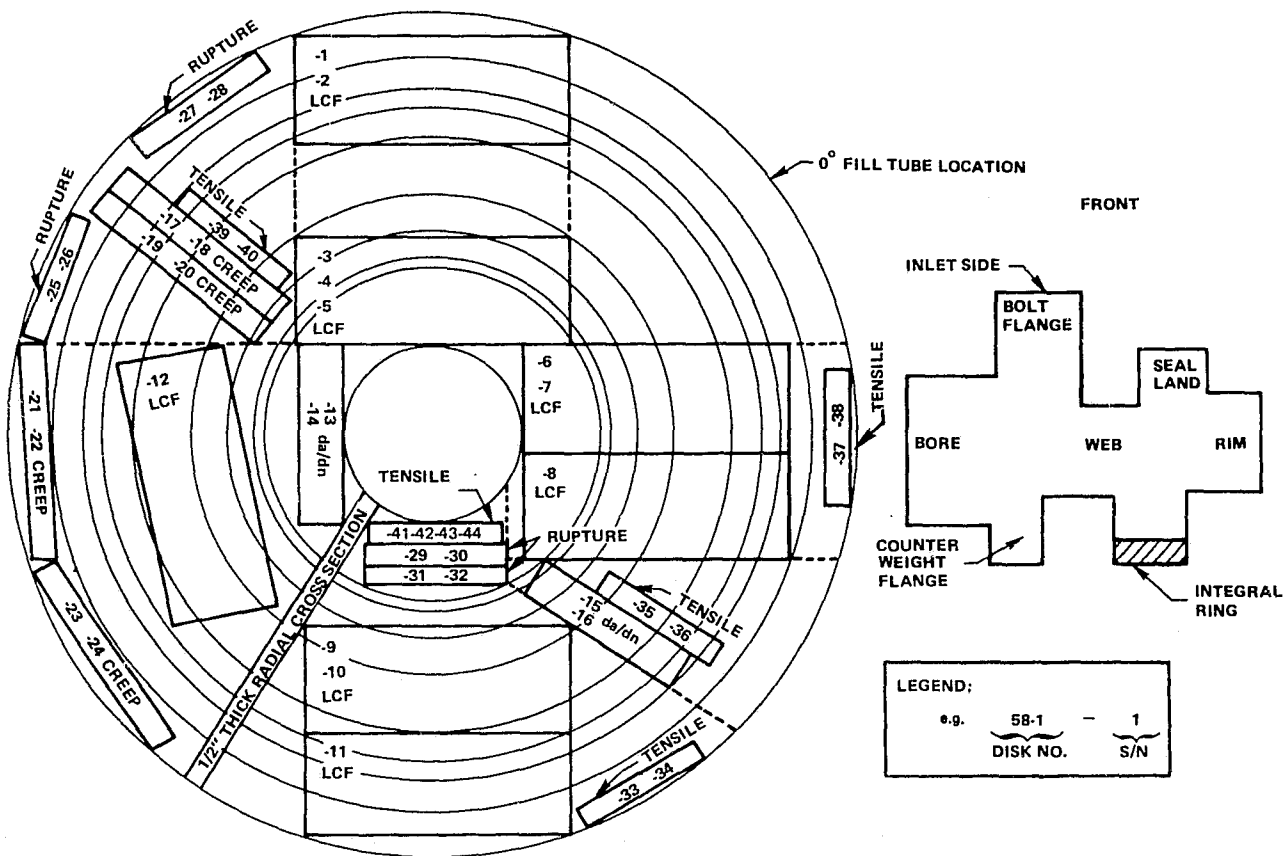


Figure 19 Identification and Location of Test Specimens Machined From Disks 58-1 and 80-1.

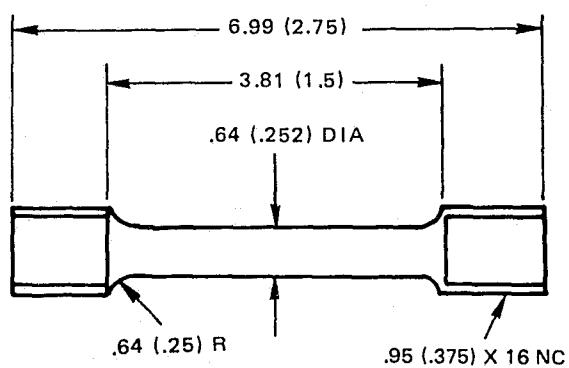


Figure 20 Tensile Test Specimen

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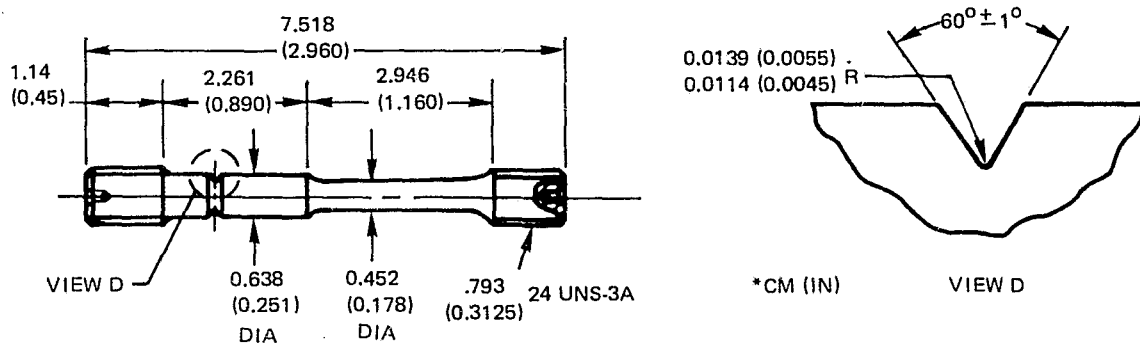


Figure 21 Combined Smooth Notch Bar ($K_t = 3.9$) Stress-Rupture Specimen

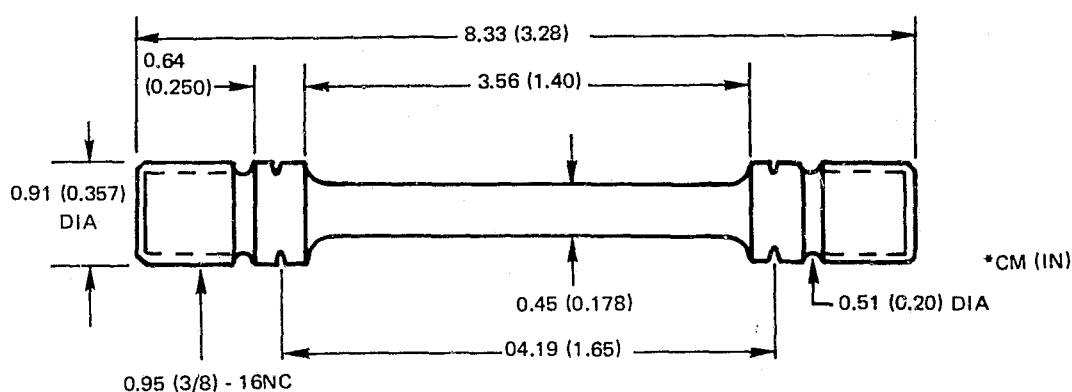


Figure 22 Creep Specimen

Fatigue crack growth specimens (Figure 23) were removed from the bore-tangential and web-radial locations of the disk. Fatigue crack growth testing (da/dN) was conducted at 454°C (850°F) and 621°C (1150°F) at a stress ratio $R = 0$ (minimum stress/maximum stress) at ten cycles per minute. The specimens were mounted in universal joint grips to assure axial loading and then tested in a hydraulic loaded fatigue machine. A resistance furnace was used to heat the specimens with controlling thermocouples placed above and below the EDM slot. The initial calculated ΔK value contained a sufficient stress to initiate and propagate a crack from the EDM slot.

$$\Delta K = \Delta \sigma \pi a f(a/b)$$

$\Delta \sigma$ = alternating gross stress applied

a = half specimen width

$f(a/b)$ = finite width correction factor by Koiter*

The crack length was measured, using an optical telescope mounted on a micrometer slide.

*Reference: Tada, H.; "A note on finite width corrections to the stress intensity factor." Engineering Fracture Mechanics, 1971, Volume 3, pages 345 to 347.

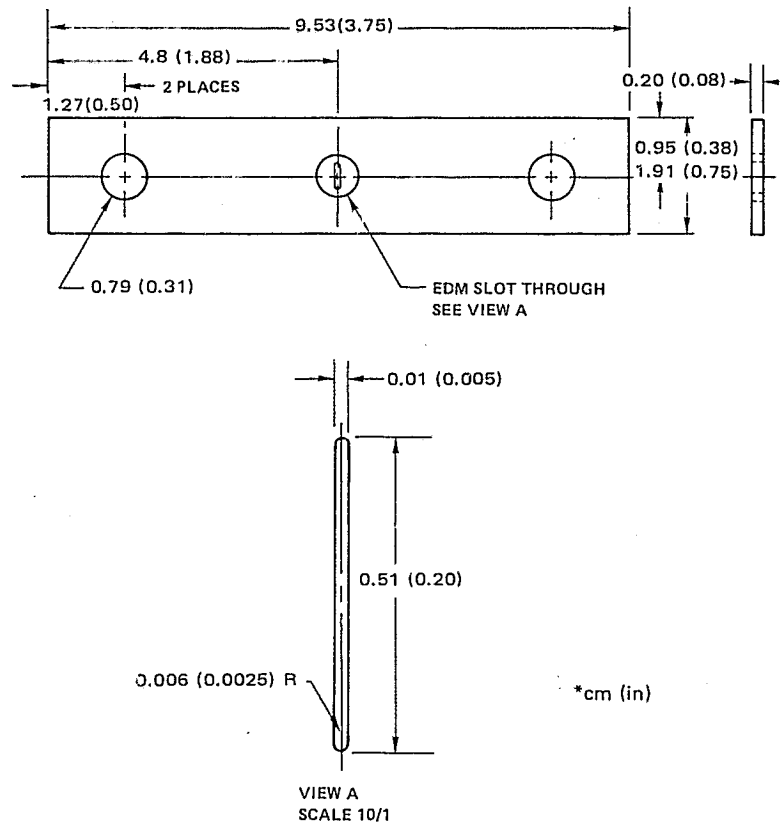


Figure 23 Fatigue Crack Growth Specimen

Notched ($K_t = 2.5$) low-cycle fatigue bolt-hole specimens (Figure 24) were removed in the tangential direction from the rim and bore and from both tangential and radial direction from the web. Low-cycle fatigue testing was conducted at 482°C (900°F), and at stress levels of 621 MPa (90 KSI), 568 MPa (85 KSI), and 552 MPa (80 KSI). A cycle of ten seconds at load and 60 seconds at no load was utilized. The cross-sectional area of each specimen was accurately measured to allow grouping of similar specimens for testing as a four specimen gang at the same stress. A single resistance furnace was used to heat all four specimens of the gang and the test temperature was monitored by attaching thermocouples to the gauge of each specimen. A photograph of the test rig is shown in Figure 25.

Tensile Properties

Tensile results showed that minimum target values were exceeded at room temperature and 538°C (1000°F) for both disks 58-1 and 80-1 as shown in Table XIV. The thinner sections of the disk (e.g., flange, integral ring, rim) displayed an approximately 35 MPa (5 KSI) higher yield and ultimate strength relative to thicker sections (e.g., web, bore) as shown in Figures 26 and 27. Metallographic examination of the fracture surfaces revealed that both room temperature and 538°C (1000°F) tensile tests failed intergranularly (Figure 28).

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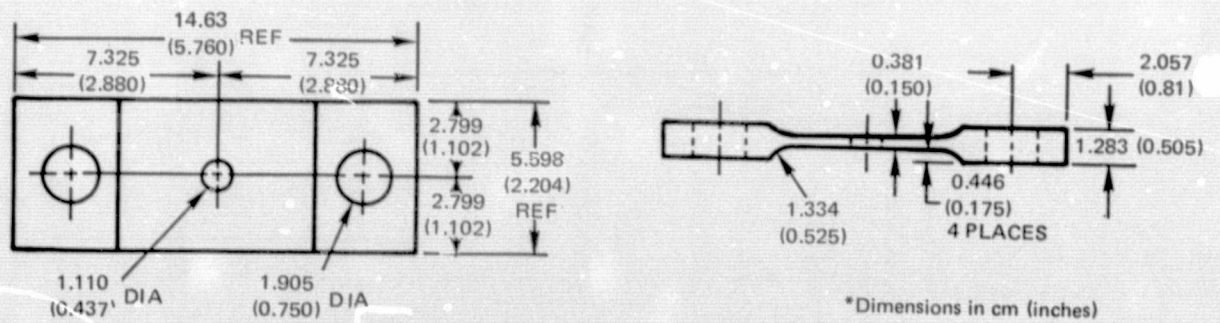


Figure 24 Bolt-Hole ($K_t = 2.5$) Low Cycle Fatigue Specimen



Figure 25 Gang Rig Used to Test Four Low Cycle Fatigue Specimens Simultaneously

TABLE XIV
TENSILE PROPERTIES

Test Temp.	Disk No.	S/N	Specimen Location and Orientation	UTS, MPa (ksi)	0.2% Y.S. MPa (ksi)	%EI	%RA
RT ↓	58-1	41	Bore-Tangential	1358 (197)	934 (135)	22.3	28.3
		43	Bore-Tangential	1345 (195)	917 (133)	25.3	29.0
		33	Rim-Tangential	1386 (201)	986 (143)	22.5	28.2
		37	Rim-Tangential	1379 (200)	965 (140)	22.8	27.6
		35	Web-Radial	1351 (196)	946 (137)	24.2	27.7
		39	Web-Radial	1351 (196)	924 (134)	24.8	29.6
	80-1	41	Bore-Tangential	1372 (199)	938 (136)	24.5	29.6
		43	Bore-Tangential	1351 (196)	924 (134)	25.9	30.8
		33	Rim-Tangential	1372 (199)	952 (138)	25.8	31.5
		37	Rim-Tangential	1372 (199)	945 (137)	22.3	23.3
		35	Web-Radial	1351 (196)	917 (133)	27.0	30.9
		39	Web-Radial	1345 (195)	931 (135)	22.9	24.3
	Target Min			1241 (180)	862 (125)	15.0	18.0
538°C (1000°F) ↓	58-1	42	Bore-Tangential	1241 (180)	841 (122)	26.0	27.6
		44	Bore-Tangential	1255 (182)	848 (123)	24.7	27.0
		34	Rim-Tangential	1282 (186)	889 (129)	21.9	26.4
		38	Rim-Tangential	1276 (185)	889 (129)	21.3	26.4
		36	Web-Radial	1248 (181)	862 (125)	27.4	26.9
		40	Web-Radial	1234 (179)	827 (120)	22.8	28.4
	80-1	42	Bore-Tangential	1262 (183)	841 (122)	25.5	29.6
		44	Bore-Tangential	1248 (181)	834 (121)	26.1	28.0
		34	Rim-Tangential	1276 (185)	889 (129)	23.4	27.7
		38	Rim-Tangential	1289 (187)	883 (128)	23.5	29.0
		36	Web-Radial	1248 (181)	862 (125)	25.9	29.8
		40	Web-Radial	1234 (179)	862 (125)	24.3	26.2
	Target Min			1103 (160)	758 (110)	15.0	18.0

Note: See Figure 19 for specimen location.

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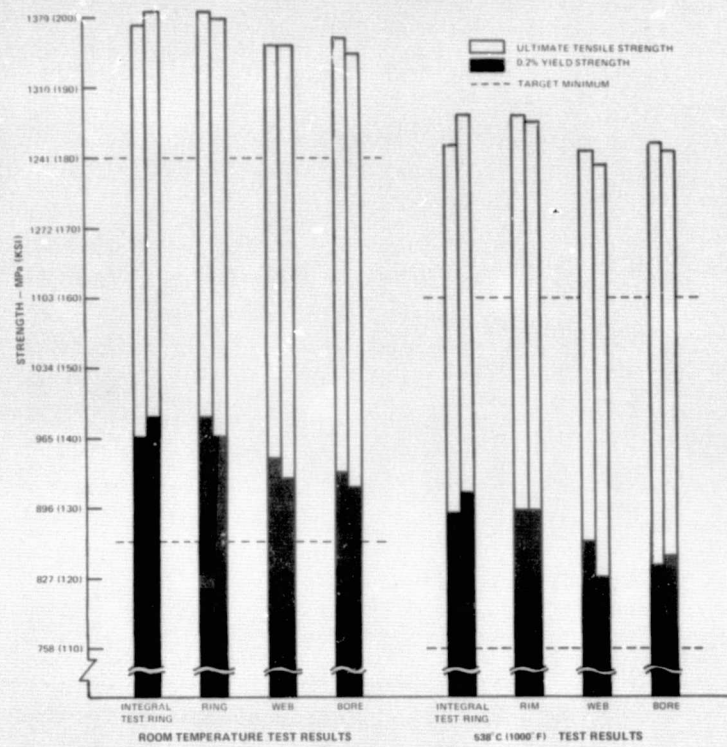


Figure 26 Tensile Strength of Disk 58-1 Showing Thinner Sections (i.e., flange, rim) to be Slightly Stronger Than Thicker Sections (i.e., web, bore)

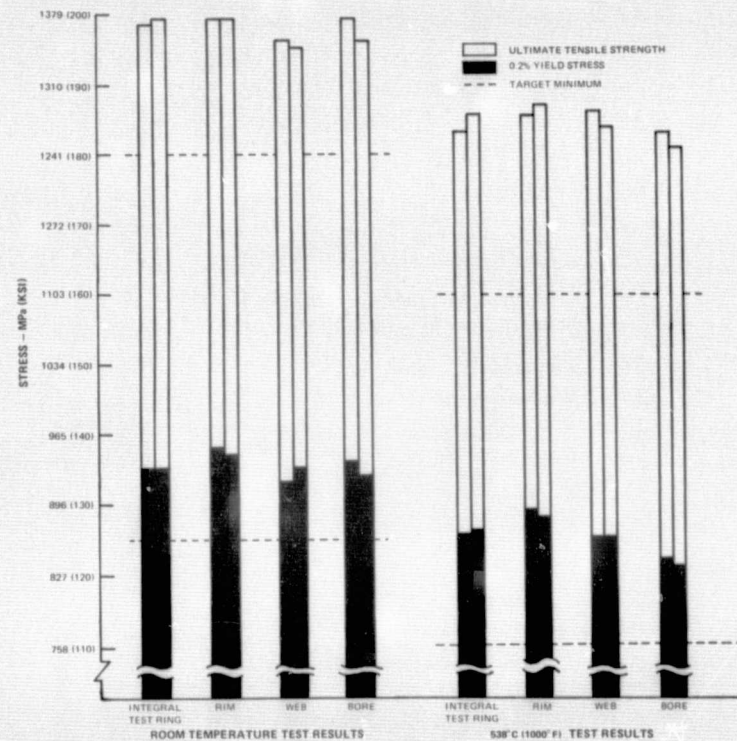


Figure 27 Tensile Strength of Disk 80-1 Showing Thinner Sections (i.e., flange, rim) to be Slightly Stronger Than Thicker Sections (i.e., web, bore)

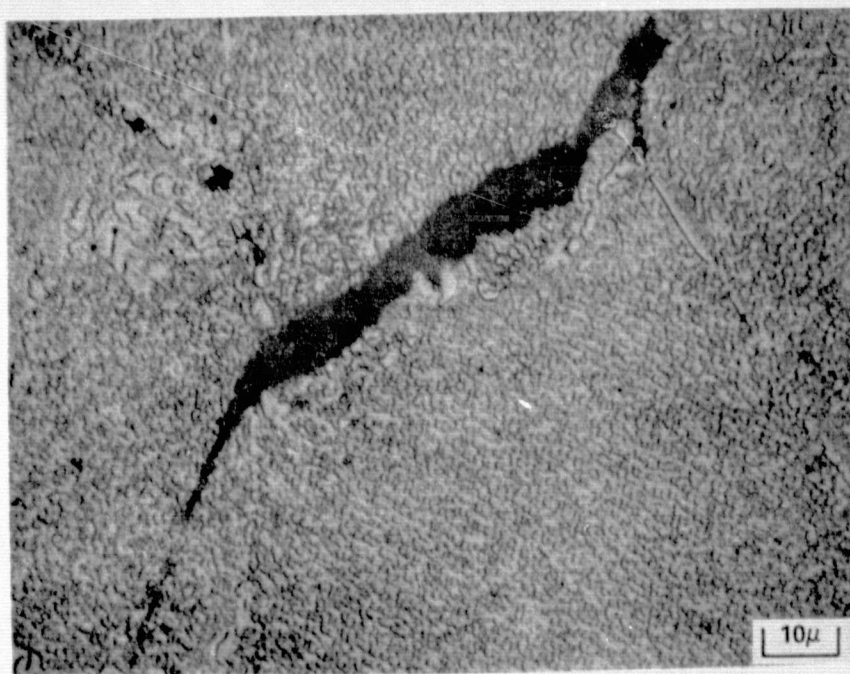


Figure 28 Photomicrographs of Tensile Specimen (S/N 58-1-41) Tested at Room Temperature Showing an Intergranular Failure Mode. Similar intergranular failure mode was also observed for the 538°C (1000°F) tensile tests.

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Stress-Rupture Properties

Stress-rupture properties are shown in Table XV and Figure 29. The rim properties were slightly superior to bore properties. The stress-rupture properties for disk 58-1 appeared to be better than those for disk 80-1 as shown in Figure 29. However, metallographic examination of the failed specimens from each disk showed no differences in microstructure or failure mode (intergranular). Photomicrographs of specimens taken from the same location of each disk (location 32 as shown in Figure 19) which were tested at identical conditions of 760°C (1400°F)/552 MPa (80 ksi) showed similar grain size and microstructure for both disks 58-1 and 80-1 (Figure 30). Furthermore, extensive optical and electron microscopy (replica) of both disks 58-1 and 80-1 revealed similar microstructural features for comparable locations as will be discussed in "Metallography" in Section 5.

TABLE XV
STRESS-RUPTURE PROPERTIES

Test Condition	Disk No.	S/N	Specimen Location and Orientation	Life hrs.	%El	%RA	Failure Location
732°C (1350°F) 621 MPa. (90 ksi)	58-1	29	Bore-Tangential	136	25.8	27.0	Smooth ↓
		30	Bore-Tangential	122	34.4	31.7	
		25	Rim-Tangential	144	27.7	30.0	
		26	Rim-Tangential	145	27.7	31.1	
	80-1	29	Bore-Tangential	99	19.5	29.8	
		30	Bore-Tangential	105	24.0	30.9	
		25	Rim-Tangential	117	21.2	30.9	
		26	Rim-Tangential	116	22.8	24.5	
760° C (1400°F) 552 MPa (80 ksi)	58-1	31	Bore-Tangential	88	25.4	28.5	Smooth ↓
		32	Bore-Tangential	92	28.4	30.1	
		27	Rim-Tangential	114	24.1	27.3	
		28	Rim-Tangential	104	24.4	26.0	
	80-1	31	Bore-Tangential	67	20.9	27.8	
		32	Bore-Tangential	65	25.1	26.9	
		27	Rim-Tangential	78	18.3	20.1	
		28	Rim-Tangential	78	20.2	24.2	

Note: See Figure 19 for specimen location.

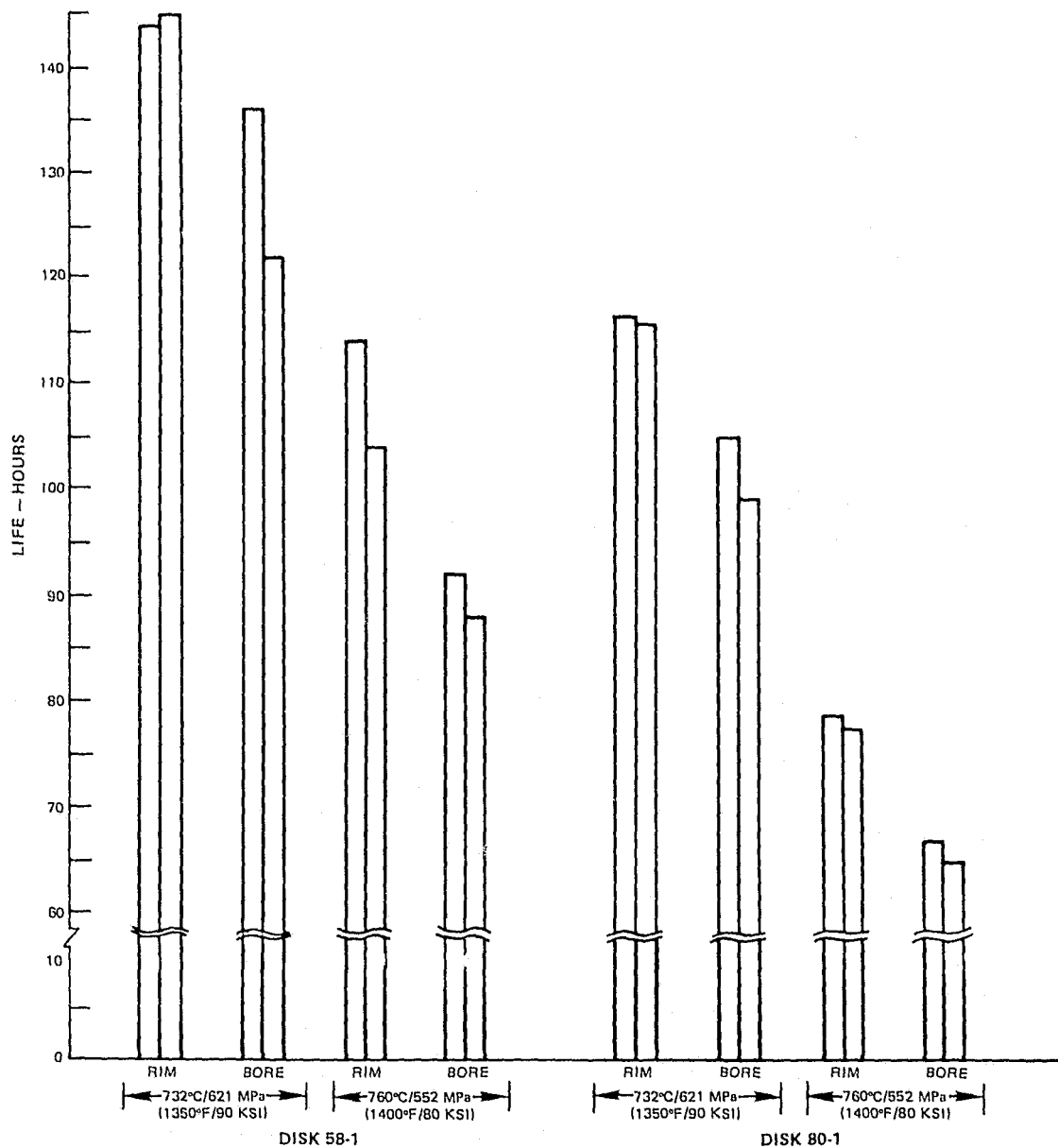


Figure 29 Stress-Rupture Results Showing That Thin Sections (rim) Were Stronger Than Thick Sections (bore).

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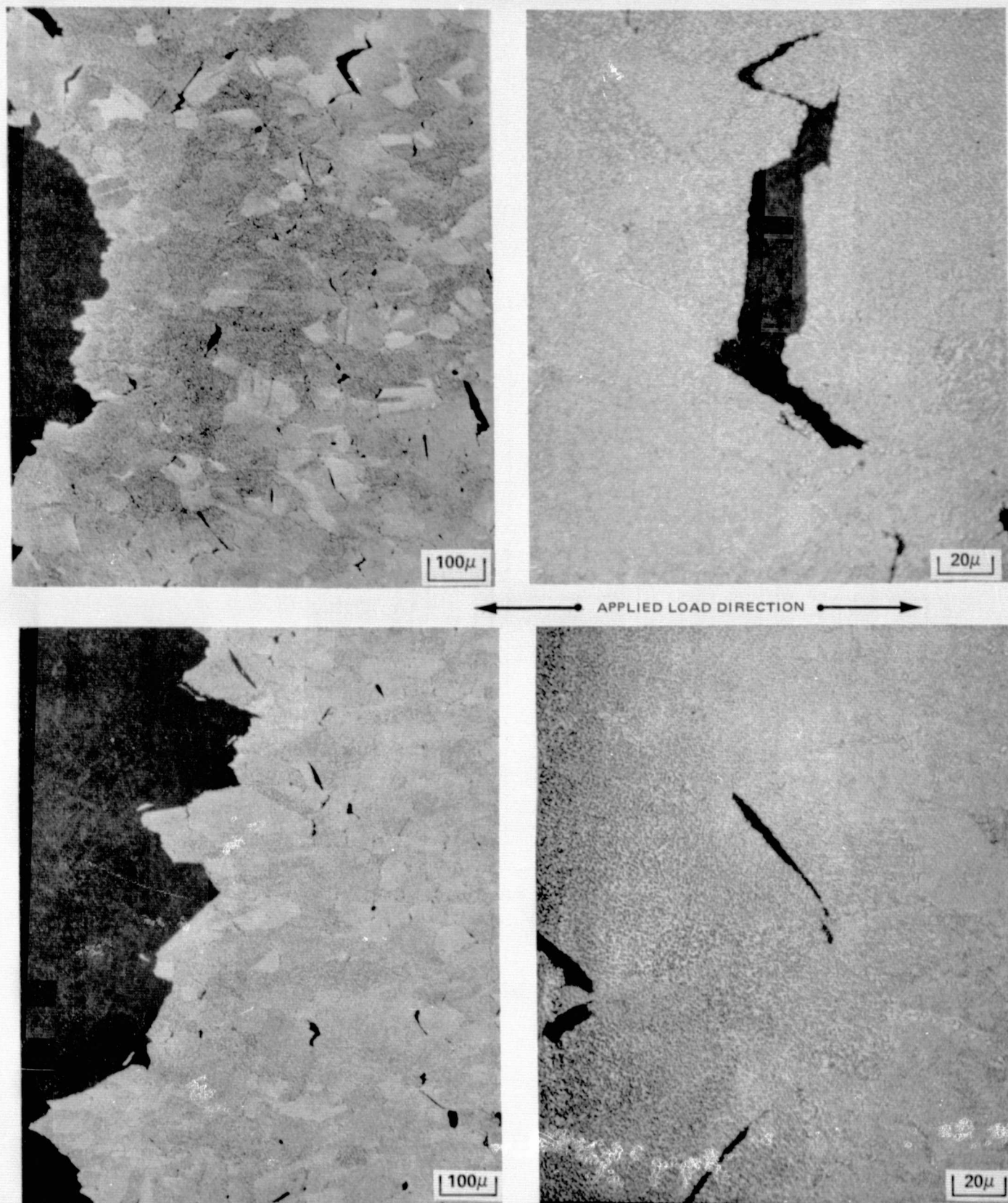


Figure 30 Photomicrographs of Stress-Rupture Specimens 58-1-32 (upper) and 80-1-32 (lower) Tested at 760°C (1400°F)/552 MPa (80 ksi). Although specimens taken from disk 58-1 exhibited higher strength, the microstructure of both disks (58-1, 80-1) was comparable.

Creep Properties

Creep testing to 0.2% creep was conducted at 649°C(1200°F)/758 MPa(110KSI) and 704°C(1300°F)/552 MPa(80KSI). The time to 0.1% and 0.2% creep was generally greater for specimens taken from the rim compared to the web as shown in Table XVI and Figure 31.

Fatigue Crack Propagation Properties

No difference in crack growth rate was observed between disks 58-1 and 80-1 as shown in Figures 32 and 33. Similar crack propagation rates were observed between specimens taken from the bore and web for the same test temperature. The growth rate at 621°C(1150°F) was faster than at 454°C(850°F). The observed crack-growth behavior is typical of earlier results obtained for direct HIP Astroloy.

The fracture surfaces of these specimens were examined by x-ray energy spectroscopy. No inclusions or porosity was observed in any of the fracture surfaces. Scanning electron micrographs of a typical fracture surface are shown in Figure 34.

Notched ($K_t = 2.5$) Low Cycle Fatigue Properties

Fatigue testing was conducted at 482°C(900°F) at a stress level of 621 MPa (90 KSI), 568 MPa (85 KSI) and 552 MPa (80 KSI). Test results indicated that disks 58-1 and 80-1 exhibited similar fatigue properties independent of orientation (tangential/radial) as shown in Table XVII. Figure 35 shows the estimated lower limit curve for HIP low carbon Astroloy, including the data of all specimens tested. The data was consistent with previously generated HIP Astroloy data.

The location of the crack initiation site was carefully identified so that scanning electron microscopy could be performed on the fracture surface. Mating fracture surfaces were examined to obtain a complete characterization of the crack initiation site. The fractographic observations for each specimen are presented in Table XVII. One or more specimens from each gang of four was examined. No anomalies were observed for crack initiations at the barrel of the bolt-hole. Figures 36 through 39 are scanning electron micrographs of selected specimens from both disks (58-1 and 80-1) showing typical fracture surfaces for such failures. Two specimens (58-1-11, 80-1-6), one from each of the two disks, contained inclusions (Al_2O_3) at the crack initiation site. Figure 40 shows S/N 80-1-6 with a 127μ (5 mil) Al_2O_3 inclusion present on the face of the specimen causing initiation to occur away from the barrel of the bolt-hole. A second sample (58-1-11) containing a 127μ (5 mil) inclusion (Al_2O_3) which also caused crack initiation away from the notch is shown in Figure 41. This Al_2O_3 inclusion is also revealed by aluminum x-ray images as shown in Figure 42. These specimens containing inclusions did not have a lower life than specimens which had a "clean" fracture surface.

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TABLE XVI
CREEP PROPERTIES

Test Condition	Disk No.	S/N	Specimen Location and Orientation	Time to	
				.1%	.2%
649°C (1200°F)/758 MPa (110 ksi)	58-1	17	Web-Radial	91 hrs.	213 hrs.
		18	Web-Radial	69	263
		21	Rim-Tangential	118	283
		22	Rim-Tangential	83	234
	80-1	17	Web-Radial	63	132.3
		18	Web-Radial	49	118.1
		21	Rim-Tangential	63	182
		22	Rim-Tangential	53	130
704°C (1300°F)/552 MPa (80 ksi)	58-1	19	Web-Radial	120	202
		20	Web-Radial	93	186
		23	Rim-Tangential	88	199
		24	Rim-Tangential	117	227
	80-1	19	Web-Radial	95	156
		20	Web-Radial	106	172
		23	Rim-Tangential	124	202
		24	Rim-Tangential	150	232

Note: See Figure 19 for specimen location.

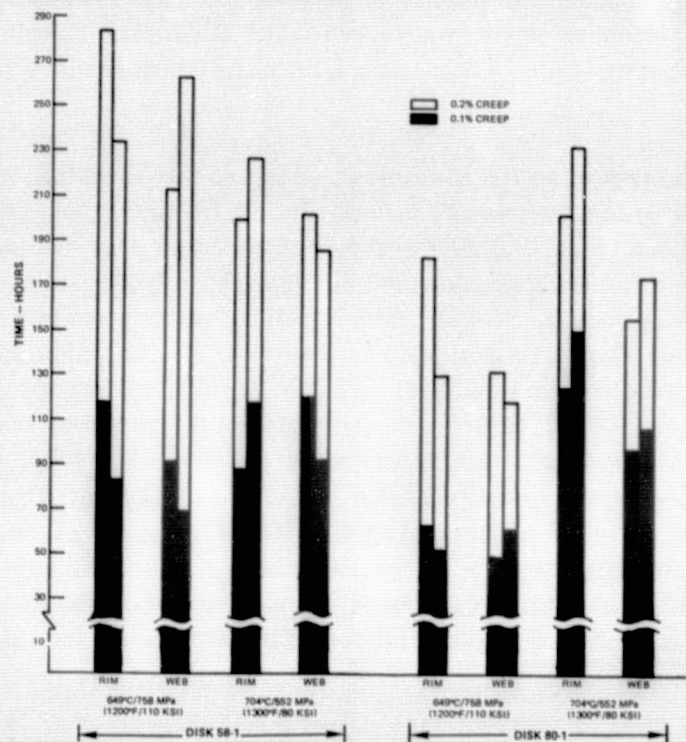


Figure 31 Creep-Rupture Properties Showing Thin Sections (rim) Strengths to be Generally Better Than That for Thick Sections (web).

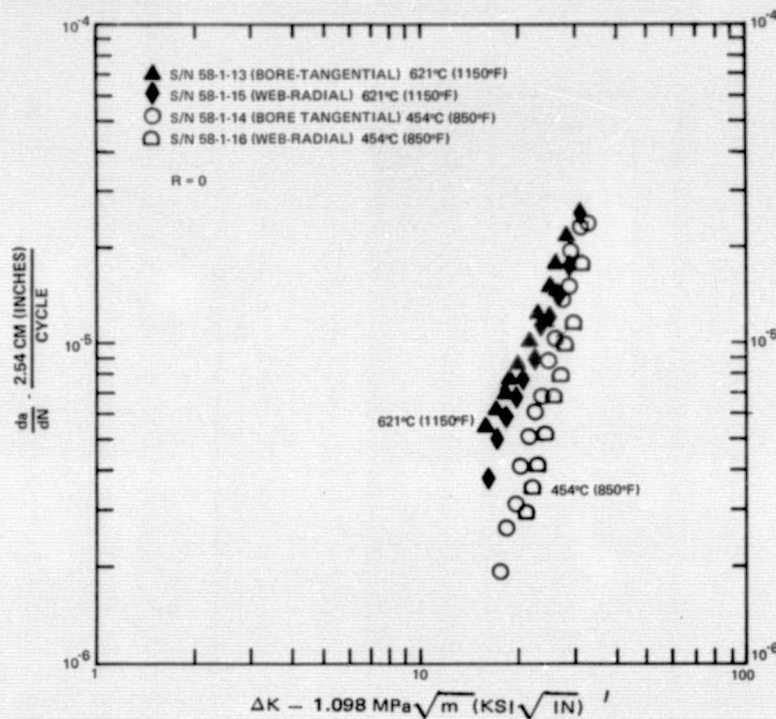


Figure 32 Fatigue Crack Growth Test Results Showing No Differences In Crack Propagation Rate Between Specimens From the Bore and Web for Disk 58-1. The observed fatigue behavior is typical for direct HIP'ed Astroloy.

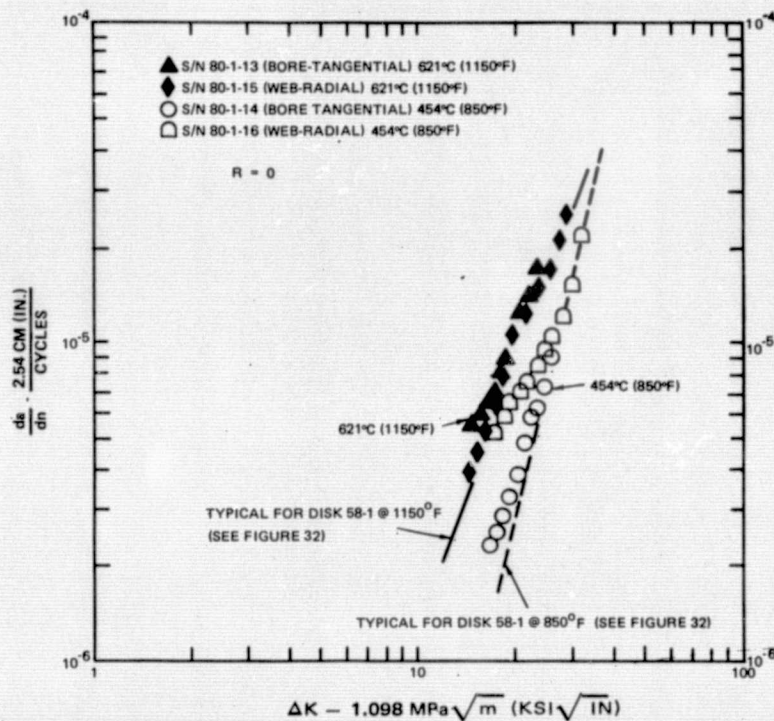


Figure 33 Fatigue Crack Growth Rate Data Showing No Difference Between Bore and Web For Disk 80-1. This data is typical for direct HIP'ed low carbon Astroloy like 58-1 as shown.

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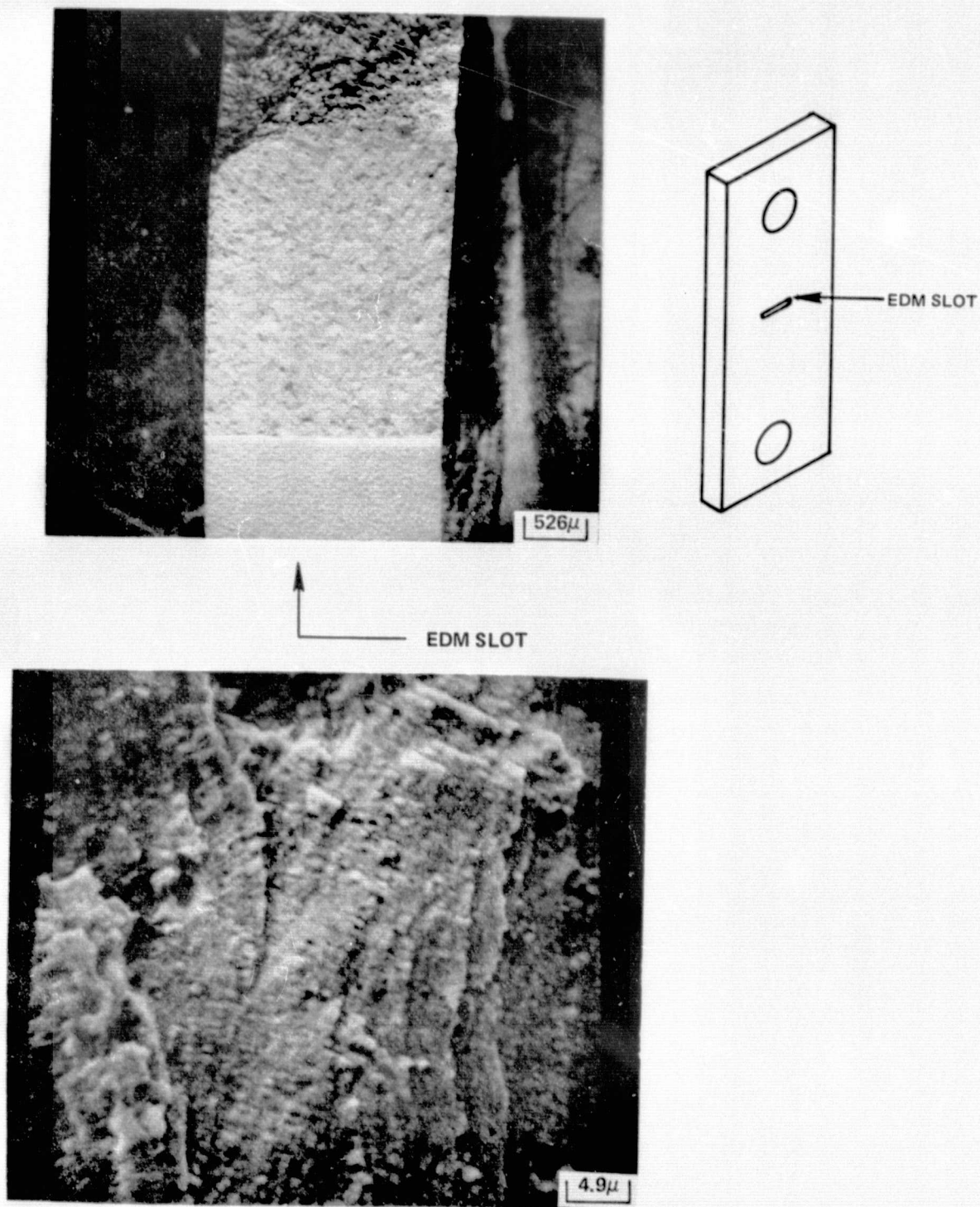


Figure 34 Scanning Electron Micrographs of a Crack Propagation Specimen Fracture Surface. This fracture surface of S/N 58-1-13 was typical of all crack propagation specimens tested, showing no inclusions

TABLE XVII

BOLT-HOLE ($K_t = 2.5$) LOW-CYCLE FATIGUE RESULTS

900° (482°C)/10 sec. at load - 60 sec. at no load

Disk No.	S/N	Location	Stress - MPa (ksi)	Cycles to		SEM Analysis of Fracture Surface
				.08 cm (1/32")	Failure	
58-1	2	Rim-Tangential	621 (90)	8,800	13,500	Normal location - no defects at origin
58-1	5	Bore-Tangential	621 (90)	8,800	14,500	Normal location - no defects at origin
58-1	7	Web-Radial	621 (90)	8,000	13,200	Normal location - no defects at origin
58-1	10	Web-Tangential	621 (90)	8,000	14,300	Normal location - no defects at origin
58-1	1	Rim-Tengential	586 (85)	46,000	54,700	Not examined
58-1	3	Bore-Tangential	586 (85)	44,000	51,000	Normal location - no defects at origin
58-1	8	Web-Radial	586 (85)	47,500	55,500	Not examined
58-1	12	Web-Tangential	586 (85)	47,000	53,400	Not examined
58-1	11	Rim-Tengential	552 (80)	22,000	27,000	Abnormal location due to 5 mil inclusion at origin
58-1	4	Bore-Tangential	552 (80)	—	D (50,000+) ⁽¹⁾	Not examined
58-1	6	Web-Radial	552 (80)	18,000	24,180	Normal location - no defects at origin
58-1	9	Web-Tangential	552 (80)	34,000	42,900	Normal location - no defects at origin
80-1	5	Bore-Tangential	621 (90)	11,000	14,600	Not examined
80-1	9	Web-Tangential	621 (90)	10,000	12,800	Not examined
80-1	11	Rim-Tengential	621 (90)	8,000	13,600	Not examined
80-1	8	Web-Radial	621 (90)	8,000	13,600	Normal location - no defects at origin
80-1	1	Rim-Tengential	586 (85)	44,000	D (50,000+) ⁽¹⁾	Not examined
80-1	3	Bore-Tangential	586 (85)	18,000	24,200	Abnormal location ⁽³⁾ - no defects at origin
80-1	6	Web-Radial	586 (85)	16,000	22,200	Abnormal origin due to 5 mil inclusion
80-1	12	Web-Tangential	586 (85)	13,500	20,800	Normal location - no defects at origin
80-1	2	Rim-Tengential	552 (80)	—	D (43,000+) ⁽¹⁾	Not examined
80-1	4	Bore-Tangential	552 (80)	—	D (43,000+) ⁽¹⁾	Not examined
80-1	10	Web-Tangential	552 (80)	—	31,300 ⁽²⁾	Abnormal origin - in grip area due to machining defect
80-1	7	Web-Radial	552 (80)	22,000	31,000	Normal location - no defects at origin

Note: (1) D = test discontinued with no failure
 (2) * = failed in grips
 (3) At corner of barrel

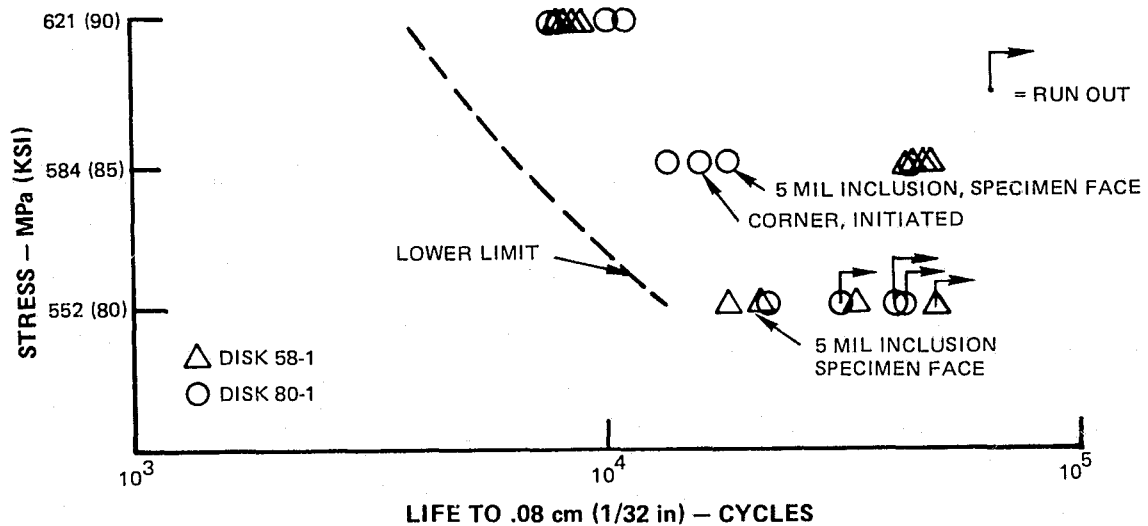


Figure 35 Low Cycle Fatigue Results of Bolt-Hole ($K_t = 2.5$) Specimens Tested at 482° (900°F) Showing Estimated Design Lower Limit

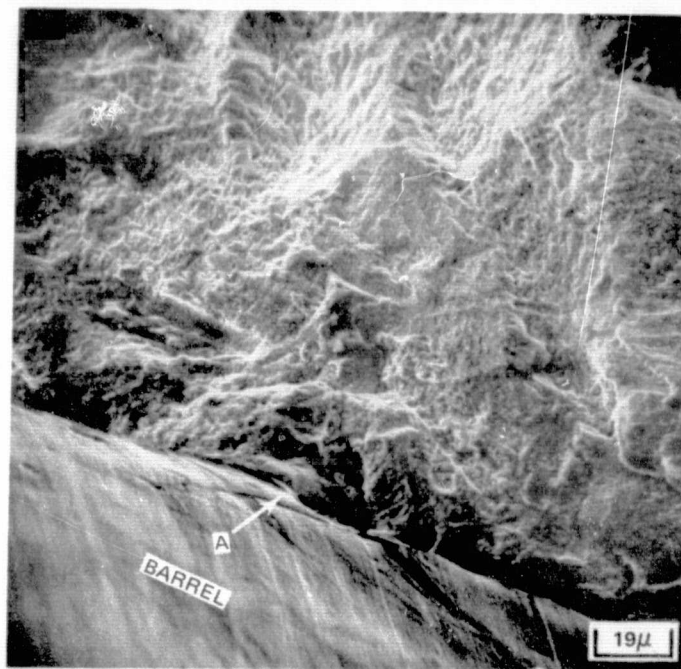
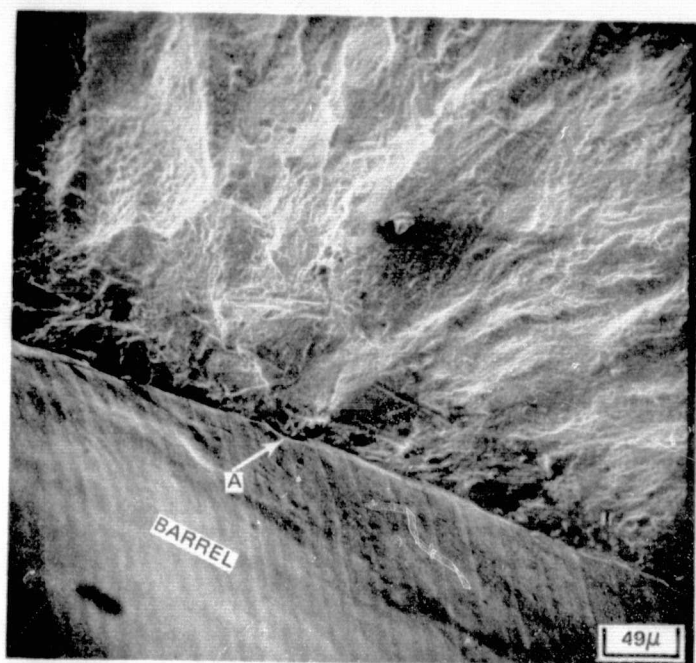
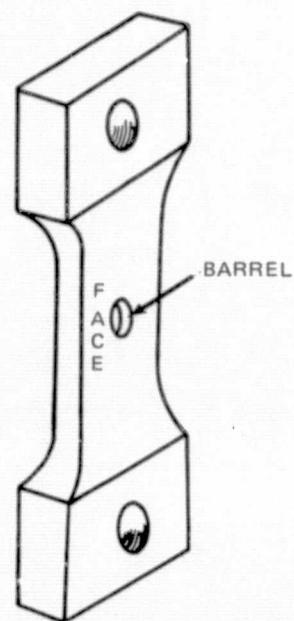
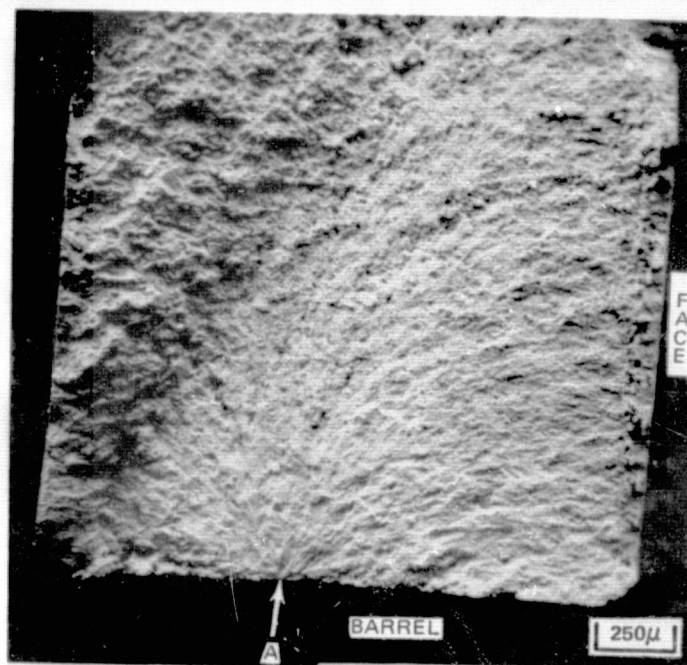


Figure 36 Scanning Electron Micrographs of S/N 58-1-5 LCF Tested At 482°C (900°F)/ 621 MPa (90 ksi) Showing the Crack Origin (A) At Barrel of Bolt-Hole. The crack initiation site is free of inclusions.

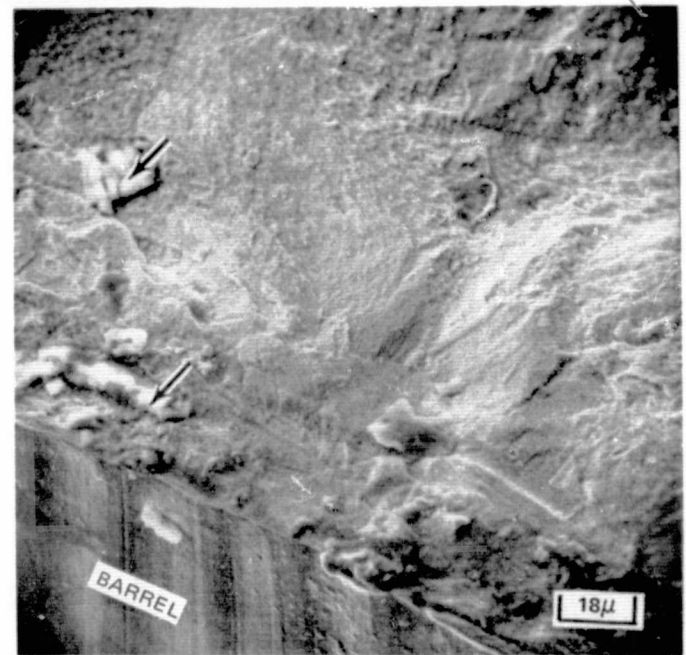
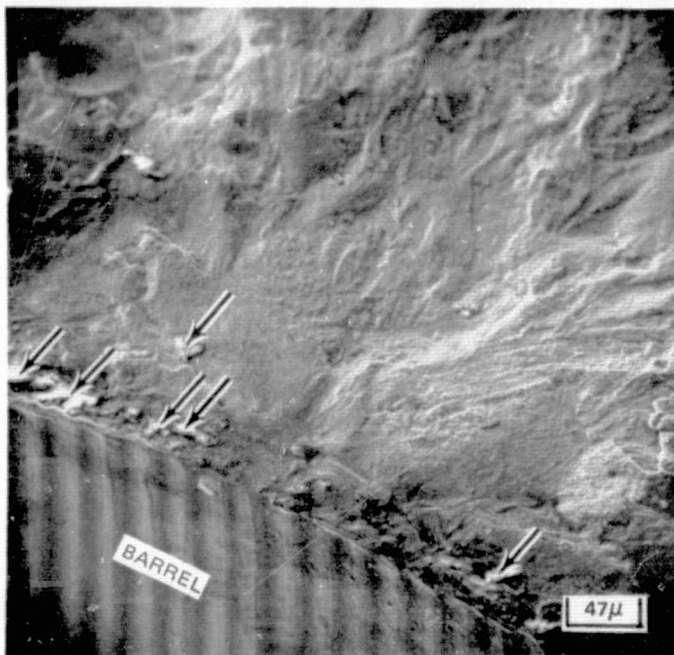
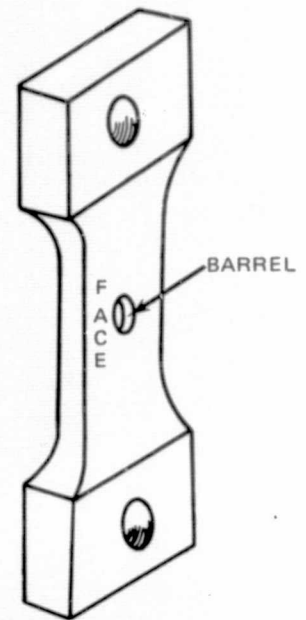


Figure 37 Scanning Electron Micrographs of S/N 58-1-3 LCF Tested At 482° (900°)/586 MPa (85 ksi) Showing Crack Origin (A) at the Barrel of the Bolt-Hole. The crack initiation site was free of any inclusions. Artifacts observed are fluorescent penetrant residues (arrows).

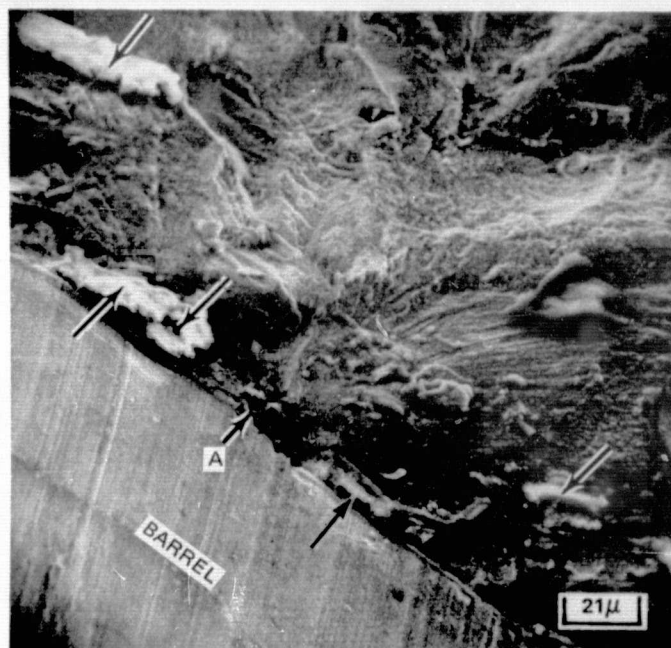
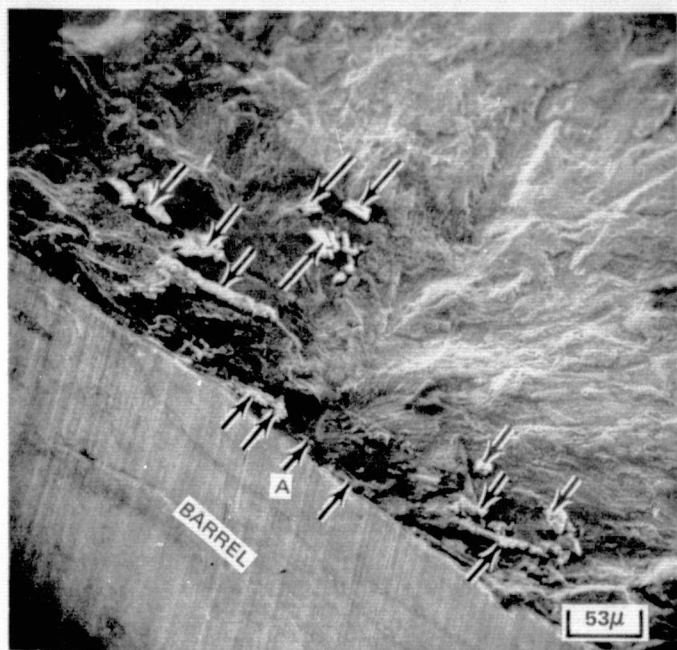
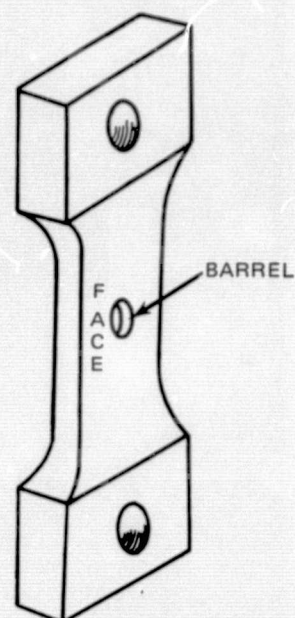
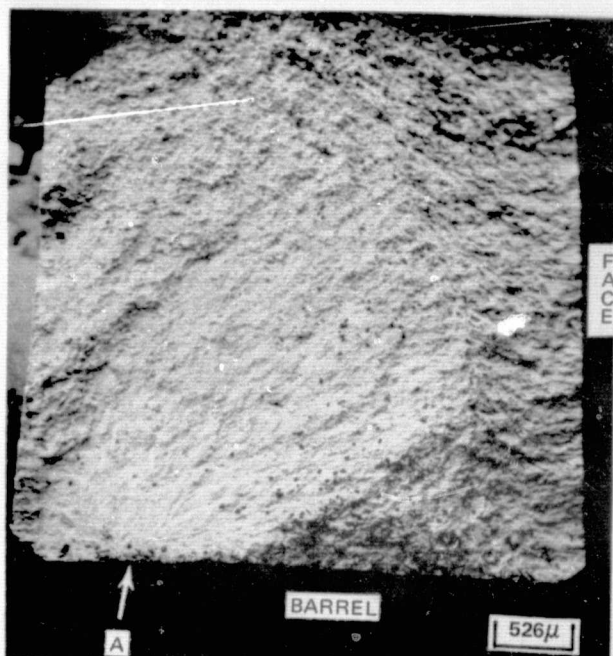


Figure 38 Scanning Electron Micrographs of S/N 80-1-8 LCF Tested At 482°C (900°F) / 621 MPa (90 ksi) Showing the Crack Origin (A) At the Barrel of Bolt-Hole. The crack initiation site is free of any inclusions. Artifacts observed are fluorescent penetrant residues (arrows).

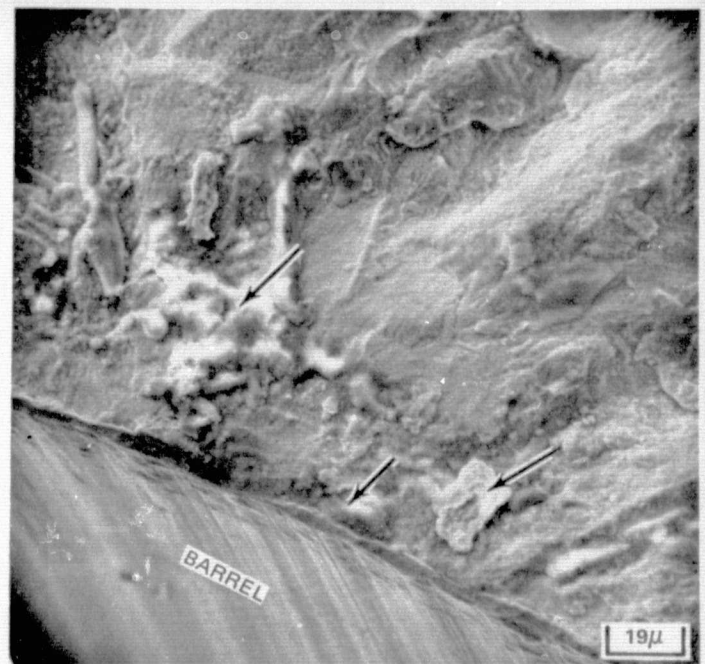
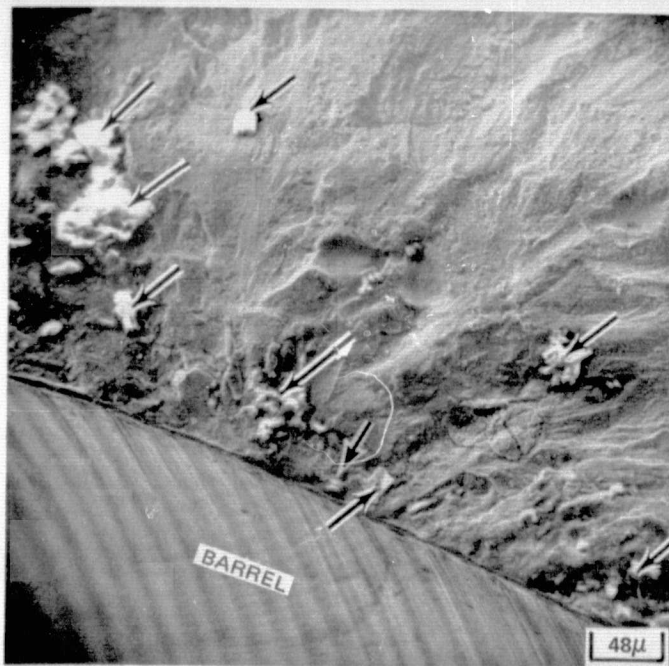
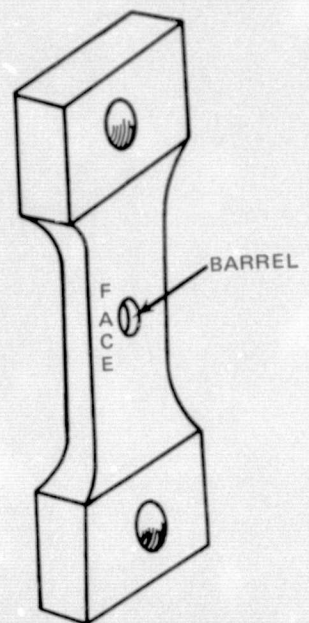


Figure 39 Scanning Electron Micrographs of S/N 80-1-7 LCF Tested At 482°C (900°F) / 552 MPa (80 ksi) Showing the Crack Origin (A) At the Barrel of the Bolt-Hole. The crack initiation site is free of any inclusions. Artifacts observed are fluorescent penetrant residues (arrows).

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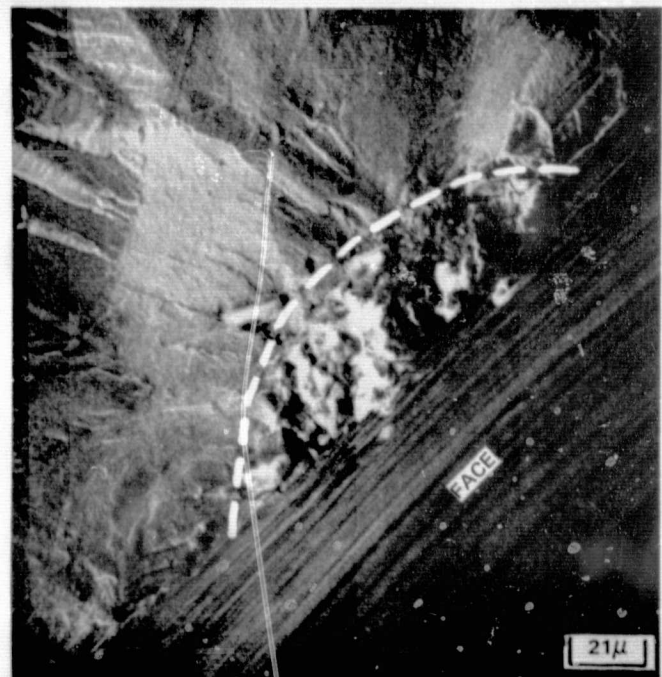
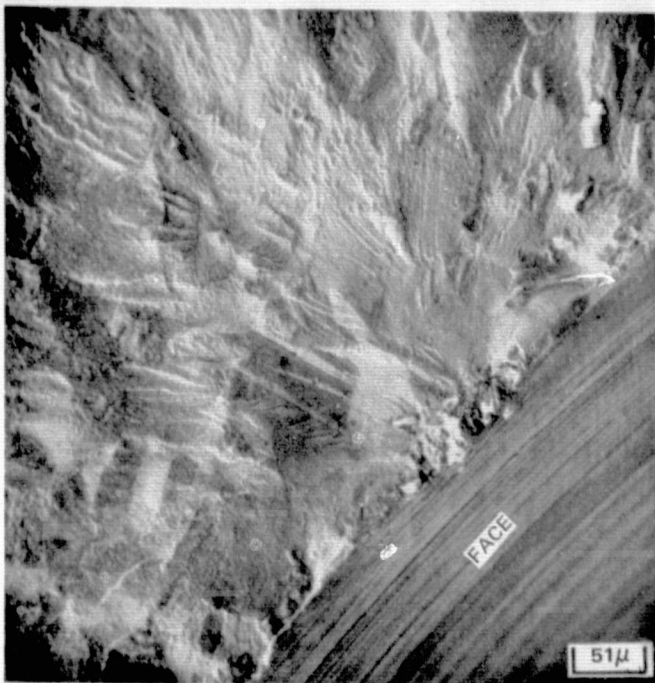
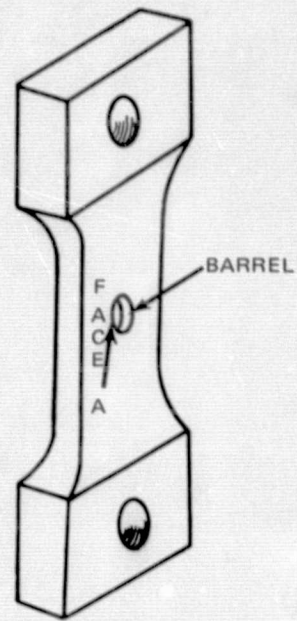
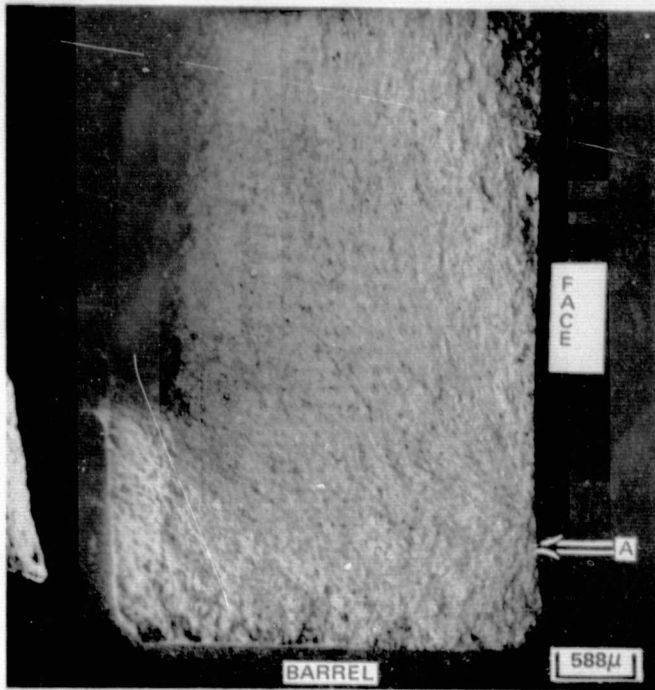


Figure 40 Scanning Electron Micrographs of S/N 80-1-6 LCF Tested At 482°C (900°F)/ 586 MPa (85 ksi) Showing the Crack Origin (A) At the Face of the Specimen Away From the Barrel of the Bolt-Hole Due to a 5 Mil (127μ) Al₂O₃ Inclusion as Outlined by Dotted Line.

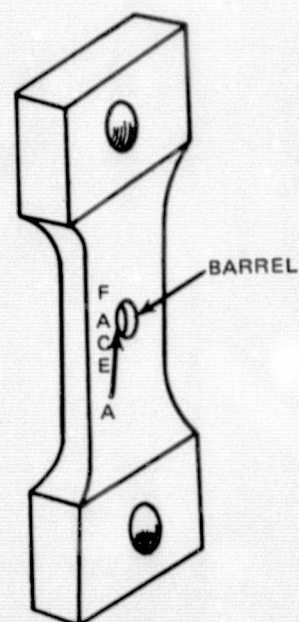
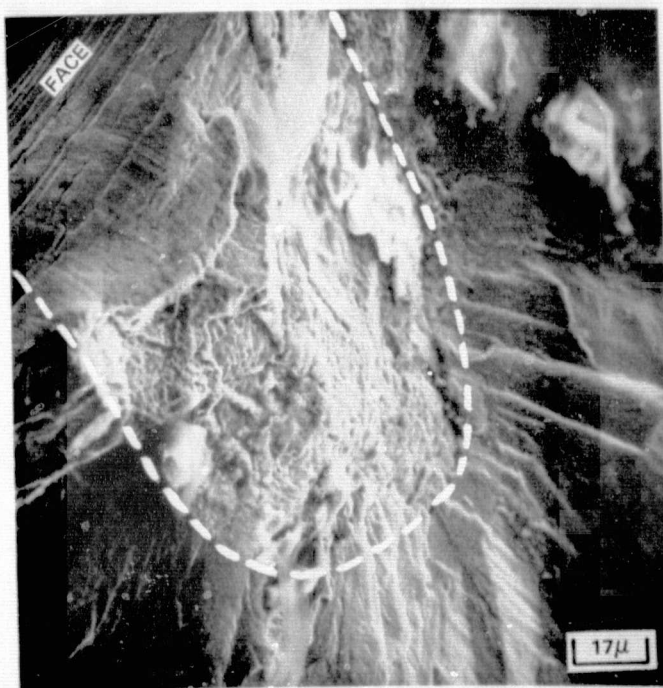
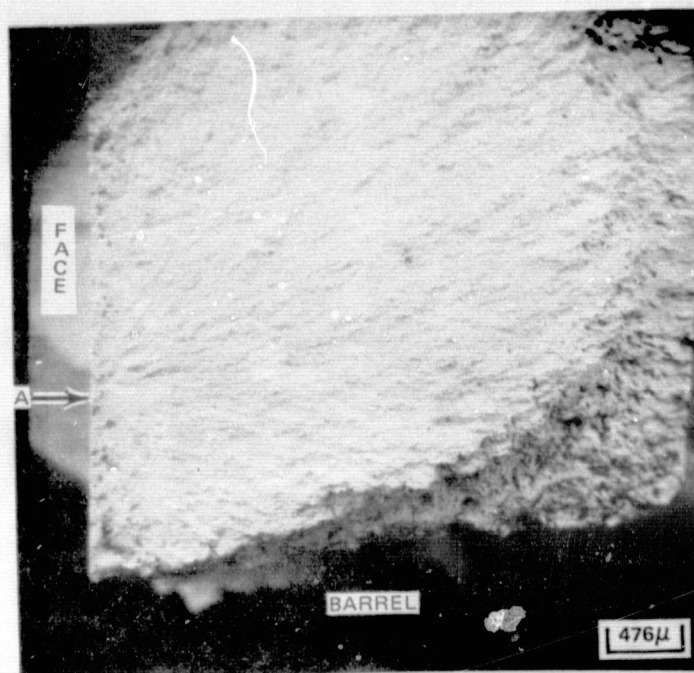


Figure 41 Scanning Electron Micrographs of S/N 58-1-11 LCF Tested At 482°C (900°F)/ 552 MPa (80 ksi) Showing the Crack Origin (A) At the Specimen Face Away From Barrel of Bolt-Hole Due to a 5 Mil (127μ) Al_2O_3 Inclusion As Outlined By Dotted Line.

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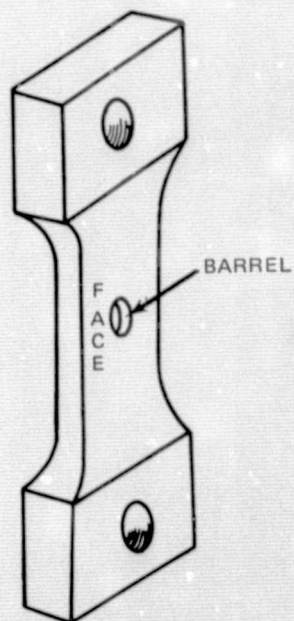
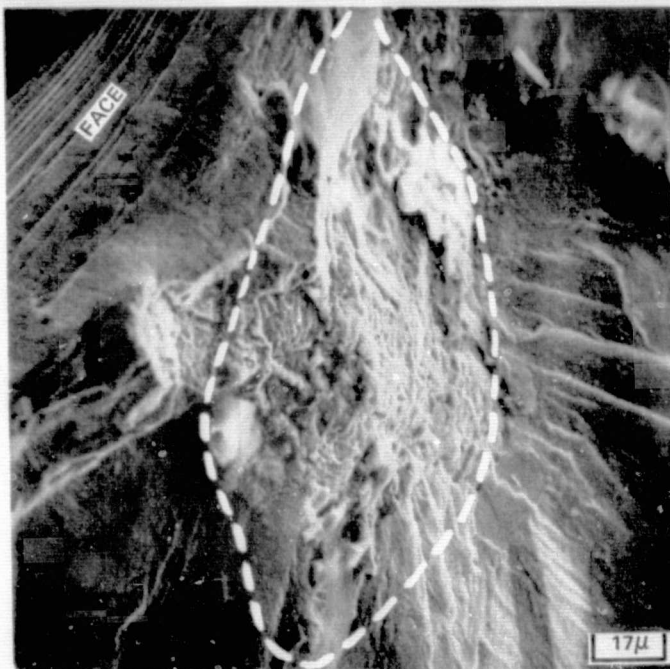


Figure 42 Scanning Electron Micrographs of S/N 58-I-11 LCF Tested At 482°C (900°F)/ 552 MPa (80 ksi) Showing a 5 Mil (127μ) Al_2O_3 Inclusion (Dotted Line) As Revealed by Aluminum X-ray Image (Upper Right).

INTERSTITIAL GAS ANALYSIS

A more detailed interstitial gas analysis was conducted for disks 58-1 and 80-1 than was initially planned because of the large scatter observed in the oxygen content data for the integral test coupon rings (Table XII) as discussed earlier in Section 3. Some of the reported oxygen content exceeded target values. The fusion analysis technique was not utilized at this point of the program because vacuum fusion analysis systems have been widely replaced by the more accurate and more efficient inert gas fusion systems. Adjacent samples for interstitial gas analysis were removed from radial sections of the disks and then submitted to P&WA - MERL⁽¹⁾ and two other test sources for comparative evaluation (Table XVIII). The results of the first set of samples taken from a radial section taken 215° clockwise from the fill tube facing the rear of the disk show generally good agreement between the analysis by Pratt & Whitney Aircraft and source A. However, a comparison between Pratt & Whitney Aircraft and source B for an additional two sets of samples from disks 58-1 and 80-1 showed a substantial difference (as large as 78 ppm) in reported oxygen content even for specimens taken adjacent to each other.

Some differences in oxygen content were noted for specimens taken from two different radial slices, 210° apart, for disk 58-1. A review of the inert gas fusion analysis techniques employed by the three laboratories showed that each used analyzers manufactured by Laboratory Equipment Corp. (LECO)-Model-TC30/36. Each laboratory appeared to have used acceptable as well as accurate procedures for sample preparation and for calibration of equipment using iron and iron-base standards supplied by both LECO⁽²⁾ and National Bureau of Standards (NBS). Nickel-base alloy standards are not available for calibration of equipment.

A round robin analysis was initiated with five laboratories, with each laboratory using its own sample preparation procedure and gas standard for calibration immediately prior to the analysis of the samples. Each laboratory utilized a LECO-Model TC30/36 analyzer. Samples were removed from various locations of disk 80-1. Adjacent samples from each location were removed and submitted to each laboratory. Included as a sample was an iron-base standard which was not identified as such. Each laboratory appeared to have used acceptable, accurate procedures for sample preparation. The results (Table XIX) reported by source C, P&WA-MERL, and P&WA-MCL⁽³⁾ were generally in agreement, while sources A and B were on the high and low end, respectively. It appears that the standards chosen to calibrate the instrument may have had an effect on results.

(1) Pratt & Whitney Aircraft - Material Engineering Research Laboratory

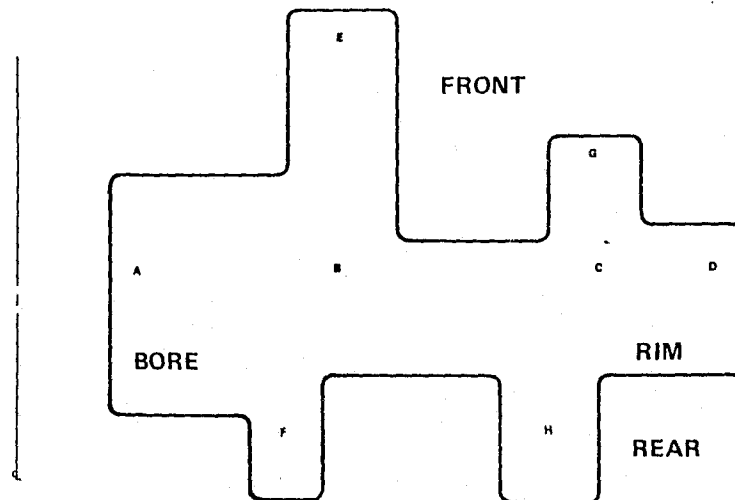
(2) Laboratory Equipment Company

(3) Pratt & Whitney Aircraft - Materials Control Laboratory

TABLE XVIII

INTERSTITIAL GAS ANALYSIS OF DISKS 58-1 AND 80-1

Disk No.	Specimen ⁽¹⁾ Location	Inert Gas Fusion Analysis By P&WA ⁽²⁾		Inert Gas Fusion Analysis By Source A		Inert Gas Fusion Analysis By Source B	
		O	N	O	N	O	N
58-1 ↓	A-I	152	23	140	--	--	--
	B-I	114	24	121	--	--	--
	C-I	122	26	117	--	--	--
	D-I	220	26	128	--	--	--
	E-I	126	22	142	--	--	--
	F-I	134	26	129	--	--	--
	G-I	116	24	140	--	--	--
58-1 ↓	B-II	103	18			62	24
	C-II	101	16			51	24
	D ₁ -II	104	18			69	27
	D ₂ -II	114	19			86	27
	E-II	104	14			58	26
	G-II	107	18			57	30
	H-II	109	18			56	27
80-1 ↓	A-I	105	19			83	25
	B-I	102	19			56	25
	C-I	114	18			52	24
	D-I	135	19			71	38
	E-I	133	22			87	24
	F-I	117	20			63	28
	G-I	127	20			49	21
	H-I	119	18			67	22



(1) Location of specimen taken from radial slice of disk as shown in Figure 19.

I = radial slice taken 215° clockwise from the fill tube facing the rear of disk.

II = radial slice taken at fill tube.

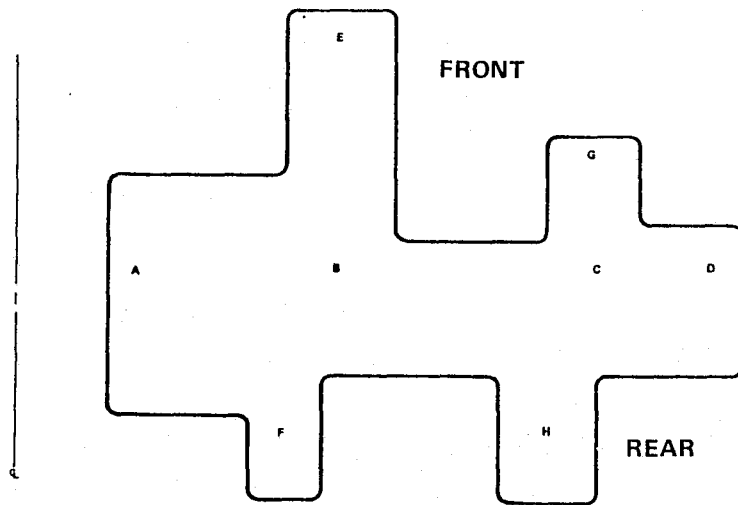
(2) Pratt & Whitney Aircraft – Materials Engineering Research Laboratory.

TABLE XIX
OXYGEN CONTENT FOR DISK 80-1, ppm

Sample Location	MERL	P&WA MCL	Source A	Source B	Source C
A	108	93	120	84	91
B	99	93	121	104	92
C	96	94	110	84	90
D	84	88	109	76	73
E	102	101	112	76	85
H	102	104	124	172	103
I*(NBS 1091)	124	123	136	100	115
Standard** Employed	146	110	153	40	185

*NBS 1091 standard was included in evaluation without being identified as such. NBS 1091 = 129 ± 8 ppm O.

**These are standards employed by each laboratory immediately prior to analyzing samples A $\rightarrow$ I.



For this reason, a second round-robin analysis was initiated using oxygen and nitrogen standards from the same lot. LECO supplied both oxygen (P/N 501-644, Lot 116) and nitrogen (P/N 501-551, Lot 114) standards. These LECO standards were taken from a coil of stainless steel wire. The homogeneity of the wire was established by determining the gas content at both ends. The wire was cut into pins and nickel plated to prevent oxidation. Multiple analysis were performed on the pin samples using National Bureau of Standards (NBS) standards for calibration. NBS 109 (15 $\pm$ 3 ppm) was used for the LECO nitrogen standard (Lot 114), while NBS 1091 (129 $\pm$ 8 ppm) was used for the LECO oxygen standard (Lot 116). These multiple results were statistically analyzed to establish the reported arithmetic mean and standard deviation.

Adjacent samples from each location were removed from the bore of disk 80-1 and submitted to the previous five laboratories plus one additional laboratory. Included as an additional sample was a stainless steel standard (NBS 1091) which was not identified as such.

Each laboratory used the same analysis procedure which included analyzing standards before and after test samples. Test samples were prepared by either filing or abrasive grinding with silicon carbide paper followed by acetone or alcohol rinsing and air drying. Detailed analysis procedures are given in Appendix C.

The results of each analysis is shown in Table XX. Test source D was the only laboratory that had to recalibrate the instrument because one reading was 2 ppm higher than the standard deviation for the oxygen standard. The reported nitrogen values were in good agreement for all laboratories. However, the nitrogen content reported by laboratory B displayed slightly more scatter than other laboratories as shown by standard deviations calculations (Table XXI). The nitrogen determinations were consistent for all laboratories with a reasonable standard deviation of 3 ppm as shown in Table XXI.

The oxygen contents reported by P&WA-MERL, P&WA-MCL, source A and source C were in agreement while laboratory D was just slightly higher and laboratory B considerably higher as shown by the arithmetic means presented in Table XXI. Although the arithmetic mean was slightly higher, the standard deviation for laboratory D was the best (0.99 ppm). The oxygen contents reported by laboratory B contained considerable scatter as evidenced by a standard deviation of 17.6 ppm.

A NBS 1091 standard (129 $\pm$ 8 ppm oxygen) was included in the analysis without being identified as such. The two laboratories (B and D) which reported oxygen content higher than others, reported an oxygen content within the tolerance of the NBS 1091 standard (Table XX). The laboratories which displayed good agreement on oxygen content for the test specimens from disk 80-1 no longer show good agreement for the analysis of the NBS 1091 standard with only P&WA-MCL meeting the tolerances. P&WA-MERL and laboratory C were below standard deviation while laboratory A was above.

TABLE XX
ROUND ROBIN GAS ANALYSIS USING SAME GAS STANDARDS FOR CALIBRATION

SAMPLE DESCRIPTION	P&WA - MERL		P&WA - MCL		A		B		C		D	
	O	N	O	N	O	N	O	N	O	N	O	N
Nitrogen Standard (34 ±3 ppm)		33		37		31		33		34		36
Lot # 114		34		34		37		34		34		35
		31		35		35		34		35		36
Oxygen Standard (111 ±6 ppm)	107		109		110		112		110		112	
Lot # 116	108		113		108		106		111		114	
	108		114		109		110		113		119	
											Recalibrate	
											112	
											108	
											110	
Sample A	94	17	90	24	98	19	121	27	95	22	100	25
Sample B	93	19	96	22	96	22	86	16	92	24	101	25
Sample C	97	16	91	23	93	20	107	21	92	24	99	26
Sample D(3)	116		126		139		120		117		123	
Oxygen Standard (111 ±6 ppm)	113		110		107		107		110		118	
Lot # 116	107		118		110		103		114		118	
	116		113		112		97		113		109	
Nitrogen Standard (34 ±3 ppm)		31		32		34		32		34		34
Lot #114		31		32		33		37		32		36
		33		31		36		34		33		36

- (1) Pratt & Whitney Aircraft - Materials Engineering Research Laboratory
 (2) Pratt & Whitney Aircraft - Materials Control Laboratory
 (3) NBS 1091 (129±8 ppm) oxygen standard included in evaluation without being identified as such.

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TABLE XXI
STATISTICAL ANALYSIS OF RESULTS OF
ROUND ROBIN GAS ANALYSIS *

Laboratory	Oxygen			Nitrogen		
	$\bar{X}$	$\bar{S}$	N	$\bar{X}$	$\bar{S}$	N
P&WA-MERL ⁽¹⁾	94.6	2.08	3	17.3	1.5	3
P&WA-MCL ⁽²⁾	92.3	3.2	3	23.0	0.99	3
A	95.6	2.5	3	20.3	1.53	3
B	104.6	17.6	3	21.3	5.5	3
C	93.0	1.7	3	23.3	1.15	3
D	100	0.99	3	25.3	0.58	3
Total For All Laboratories	96.7	7.7	18	21.8	3.35	18
Total for All Laboratories Except C	95.1	3.3	15	21.9	3.04	15

$\bar{X}$ = arithmetic mean

$\bar{S}$ = standard deviation

N = Number of Samples

(1) Pratt & Whitney Aircraft - Materials Engineering & Research Laboratory

(2) Pratt & Whitney Aircraft - Materials Control Laboratory

*See Table XX for raw data.

Additional oxygen analysis was performed by P&WA-MERL on Disk 80-1 to determine if any gradient near the HIP surface existed. Specimens were removed from .076cm (0.030 in.) to 3.81 cm (1.50 in.) below the as-HIP + heat treated surface. A series of specimens from both the rim and bore were evaluated. No appreciable oxygen gradient was observed between the as-HIP surface to 3.81 cm (1.50 in.) below the surface as shown in Table XXII. The maximum oxygen content determined in each series of tests was that for the specimen taken closest to the surface, exceeding the target maximum of 100 ppm in both rim and bore locations. For the series of specimens taken at the rim, the surface oxygen was 1.5 standard deviations (1.5σ) above mean for the scan, but less than 1σ above the limit. For the bore series, however, the maximum surface content of 112 ppm was $+2\sigma$ above mean and $+3\sigma$ above the target oxygen limit of 100 ppm.

It appears that the reported oxygen gas content varies depending upon laboratory and gas standard used for calibration. Although oxygen levels have been reported as high as 172 ppm (e.g., disk 80-1) without compromising mechanical properties, a more extensive evaluation is necessary to determine the effect of high oxygen levels on properties.

METALLOGRAPHY

A radial section, 215° clockwise from the fill tube facing the rear of the disk, was removed from disk 58-1 and 80-1 for metallographic evaluation. Additional samples from the bore (thick section) and rim (thin section) of each disk was removed adjacent to this radial section to determine the effect of each heat treatment step on the microstructure. Optical microscopy revealed the grain size (ASTM4-7) to be generally uniform throughout the radial disk section for both disks as shown schematically in Figure 43. Replica electron microscopy of each of these revealed no significant microstructural differences. For this reason, sections representative of thick (bore) and thin (flange) sections were heat treated to determine the microstructural response to each heat treatment step. Figures 44 and 45 show micrographs of the as-HIP microstructure containing coarse irregular primary gamma prime which precipitated during the slow cooling rate from the HIP temperature. Heat treating at 1116°C (2040°F) solutioned and coarsened some of the gamma prime leaving a cuboidal shape gamma prime approximately 1 μm in size (Figure 46). Heat treating at 871°C (1600°F) and 982°C (1800°F) precipitated additional cuboidal-shaped gamma prime approximately 0.3 - 0.5 μm in size as shown in Figures 47 and 48. Aging at 649°C (1200°F) and at 760°C (1400°F) precipitated an extremely fine gamma prime (0.05 μm) which is barely resolvable at 12,400X as shown in Figure 49-50. Resolution of this extremely fine gamma prime (0.05 μm) would have required thin foil microscopy which was not within the scope of this program. In addition to the three gamma prime sizes (1 μm , 0.3 - 0.5 μm , 0.05 μm), there are discrete carbides and borides present primarily in the grain boundaries as shown in Figure 51. Replica electron microscopy did not reveal any significant microstructural differences between the thick (bore) and thin (rim) sections. However, it is probable that the amount of fine unresolvable precipitated gamma prime was greater in thin (rim) section than thick (bore) section which would account for the observed relationship between section size and strength. A thin section cools more rapidly than a thicker section resulting in less gamma prime precipitation during cooling and therefore more fine gamma prime (0.05 μm).

CHEMICAL ANALYSIS

The chemical composition and density of each HIP disk consolidation were determined as shown in Table XXIII. Target chemistries were met.

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TABLE XXII
OXYGEN GAS ANALYSIS OF NEAR SURFACE SPECIMENS
REMOVED FROM DISK 80-1

Specimen Identification	Approximate Distance from Surface — cm (in)	Oxygen Content — ppm
NBS Oxygen Standard — 141 ± 8 ppm		142 145
Rim - 1	.076 (0.030)	104
Rim - 2	.64 (0.25)	99
Rim - 3	1.27 (0.50)	87
Rim - 4	1.91 (0.75)	96
Rim - 5	3.18 (1.25)	92
Rim - 6	3.81 (1.50)	88
Arithmetic Mean		94.3
Standard Deviation		6.6
NBS Oxygen Standard Retest — 141 ± 8 ppm		139
Bore - 1	.076 (0.030)	112
Bore - 2	.64 (0.25)	105
Bore - 3	1.27 (0.50)	103
Bore - 4	1.91 (0.75)	101
Bore - 5	3.18 (1.25)	100
Bore - 6	3.81 (1.50)	105
Arithmetic Mean		104.3
Standard Deviation		4.3

TABLE XXIII
ALLOY CHEMISTRY AND DENSITY OF HIP ASTROLOY DISKS

Element	50-2	58-1	58-2	80-1	80-2	Target
Cr	14.8	15.0	14.8	15.1	15.4	14.0-16.0
Co	16.8	16.8	16.7	17.0	16.9	16.0-18.0
Mo	5.0	4.9	5.1	5.2	5.2	4.5-5.5
Ti	3.4	3.4	3.4	3.4	3.4	3.35-3.65
Al	3.9	3.9	4.0	4.0	4.0	3.85-4.15
B	0.018	0.023	0.020	0.024	0.021	0.02-0.03
C	0.022	0.024	0.022	0.024	0.024	0.02-0.06
P	< 0.002	< 0.002	< 0.002	< 0.002	< 0.002	< 0.015
Zr	< 0.001	< 0.001	< 0.001	< 0.01	< 0.01	< 0.06
Si	0.05	0.04	0.06	0.065	0.065	< 0.20
Fe	0.07	0.10	0.08	0.08	0.08	< 0.50
Mn	0.001	< 0.001	< 0.002	< 0.001	< 0.001	< 0.15
W	< 0.15	< 0.05	< 0.05	< 0.01	< 0.01	< 0.05
Cu	< 0.01	< 0.05	< 0.01	< 0.01	< 0.01	< 0.10
Pb	< 1 ppm	< 1 ppm	< 10 ppm	< 1 ppm	< 1 ppm	< 10 ppm
Bi	< 0.3 ppm	< 0.3 ppm	< 0.3 ppm	< 0.5 ppm	< 0.5 ppm	< 0.5 ppm
Ni	R	R	R	R	R	R
Density	8.04 g/cm ³	8.03 g/cm ³	7.99 g/cm ³	8.02 g/cm ³	8.01 g/cm ³	

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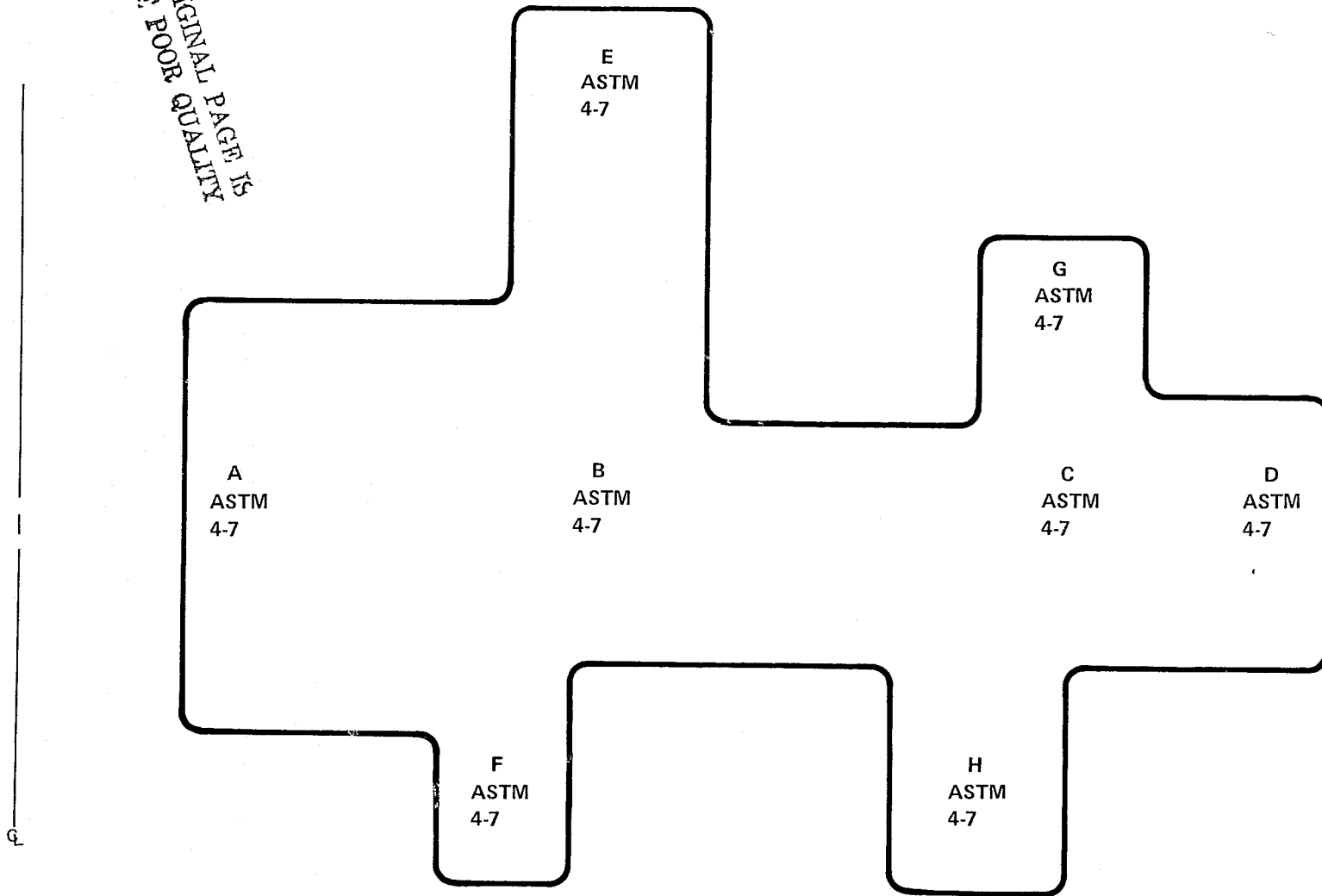


Figure 43 Schematic Diagram of a Radial Section Removed From Disk 58-1 and 80-1
Showing Grain Size (ASTM 4-7) to be Generally Uniform Throughout the Disk

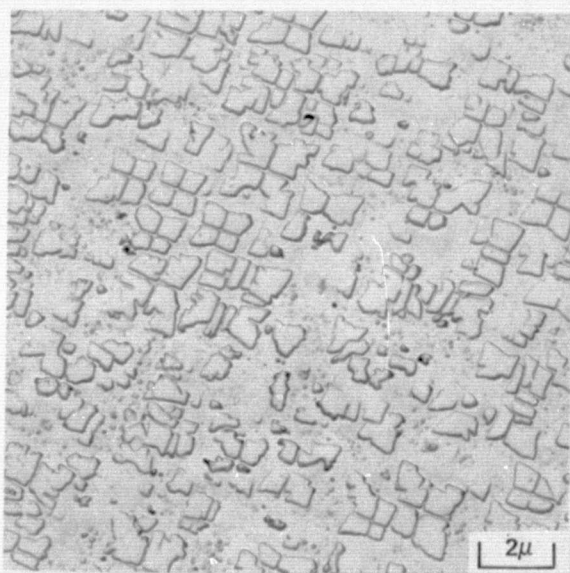
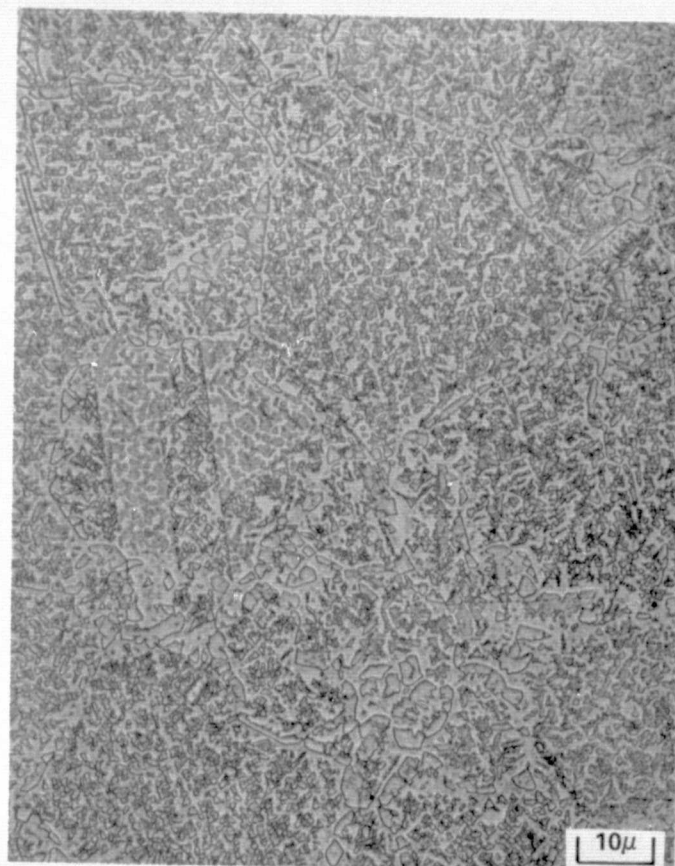


Figure 44 Micrographs of the Bore (thick section) of As-HIP Low Carbon Astroloy Showing Coarse Irregular Shaped Primary Gamma-Prime which precipitated During the Slow Cooling Rate from the HIP Temperature.

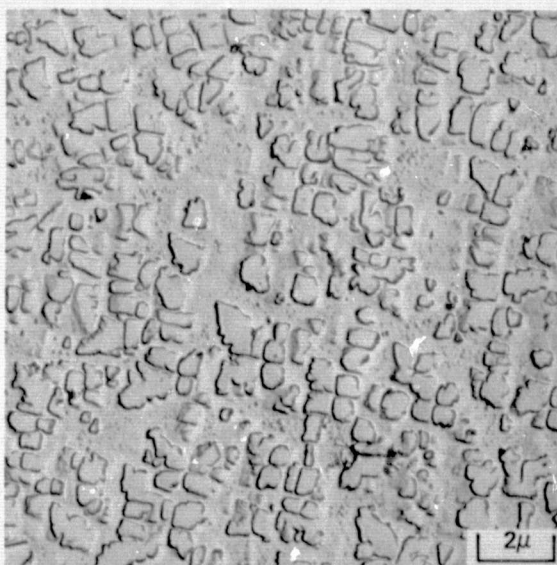
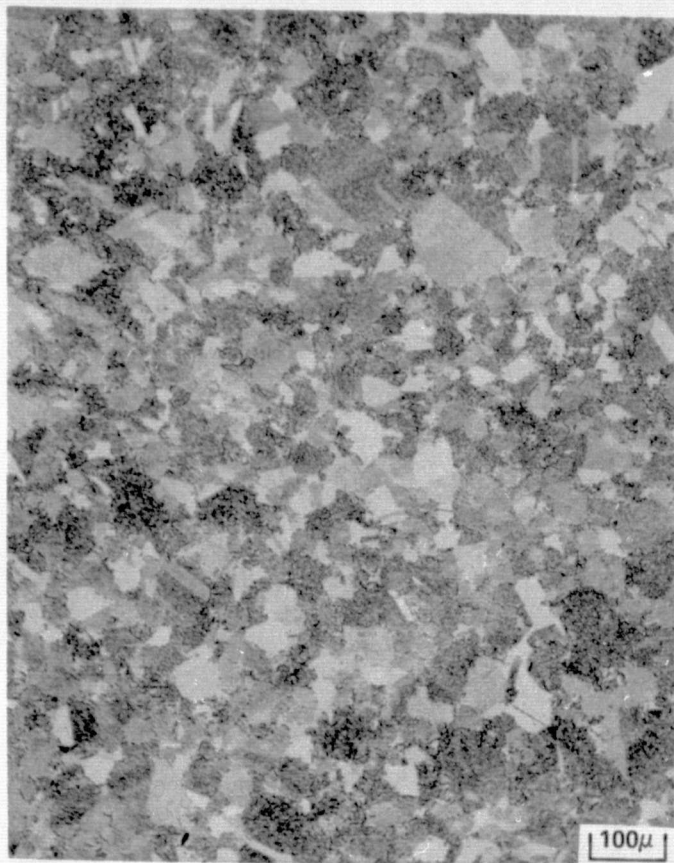
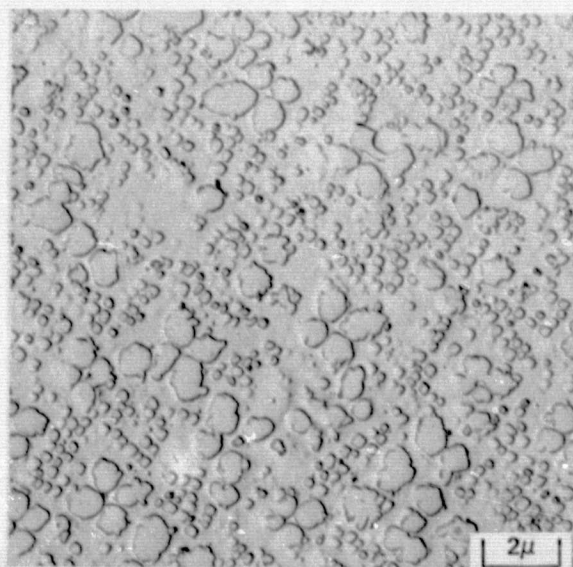
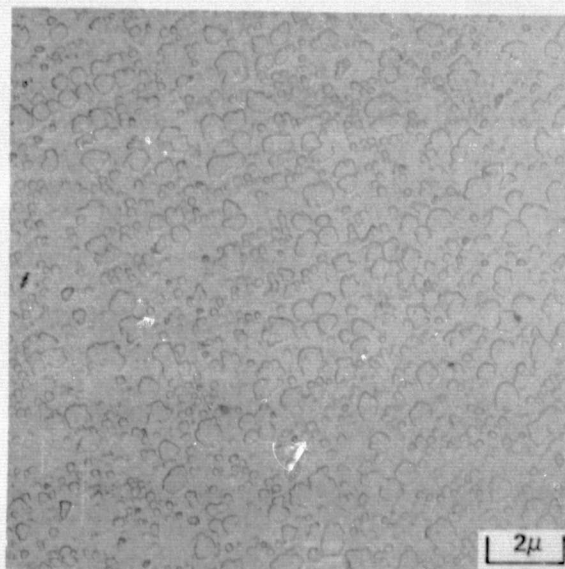


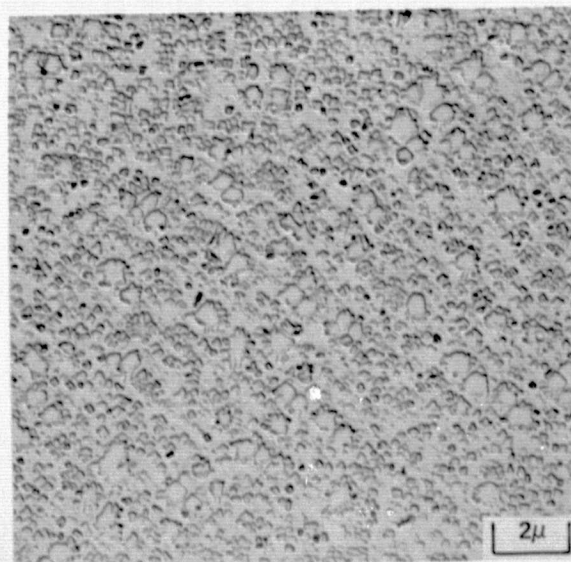
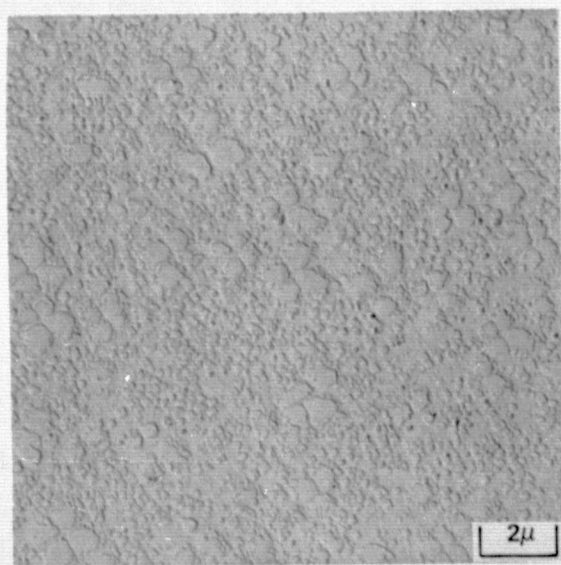
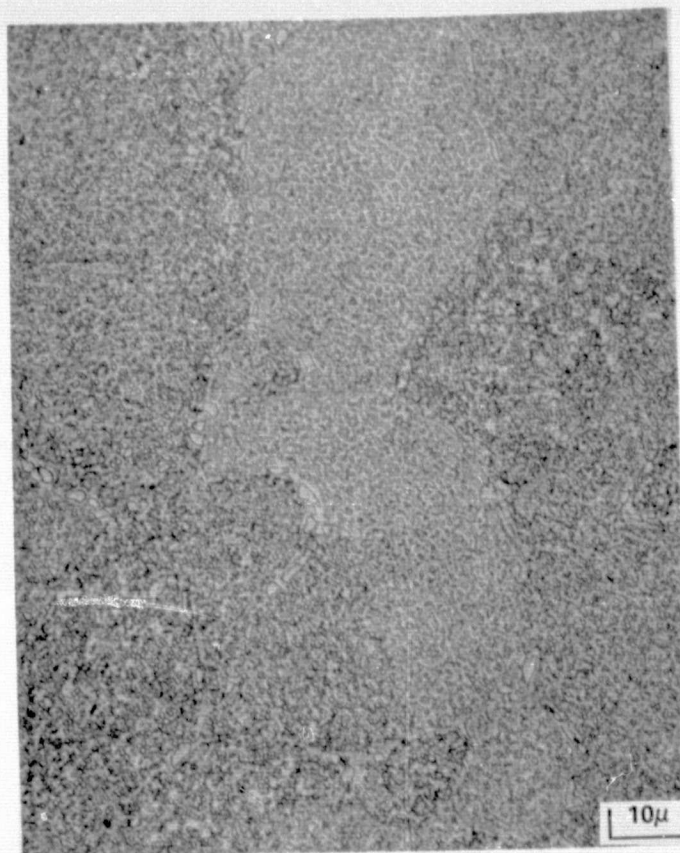
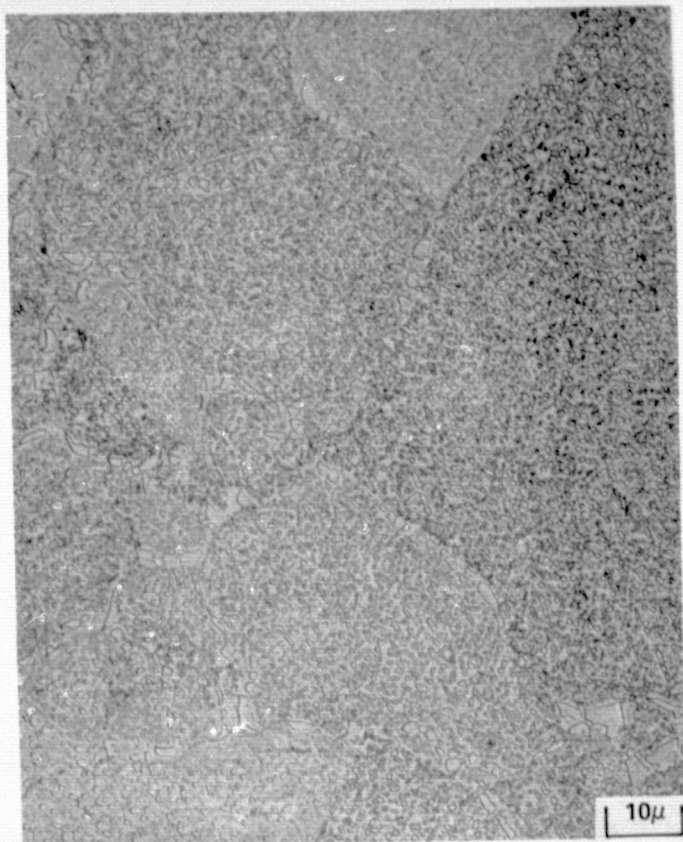
Figure 45 Micrographs of the Flange (Thin Section) of As-HIP Low Carbon Astroloy Showing Coarse, Irregular Shaped Primary Gamma-Prime Which Precipitated During the Slow Cooling Rate from the HIP Temperature



THICK

THIN

Figure 46 Micrographs of HIP Low Carbon Astroloy Solutioned At 1116°C (2040°F) Showing No Significant Difference Between Thin and Thick Sections. This heat treatment solutioned and coarsened some of the gamma prime leaving a cuboidal shape gamma-prime approximately 1 μ in size.

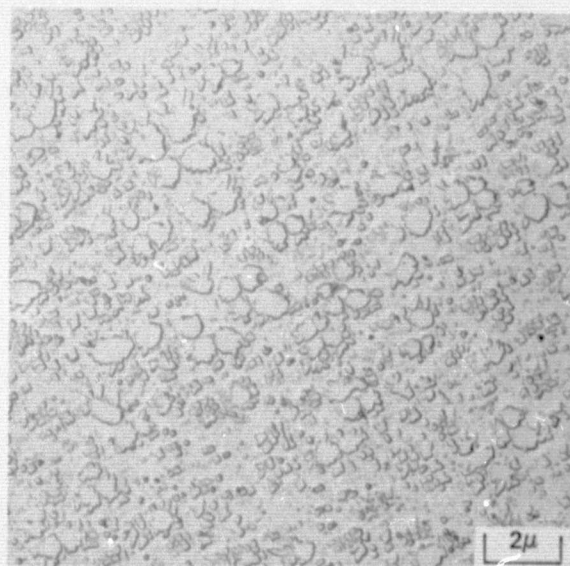
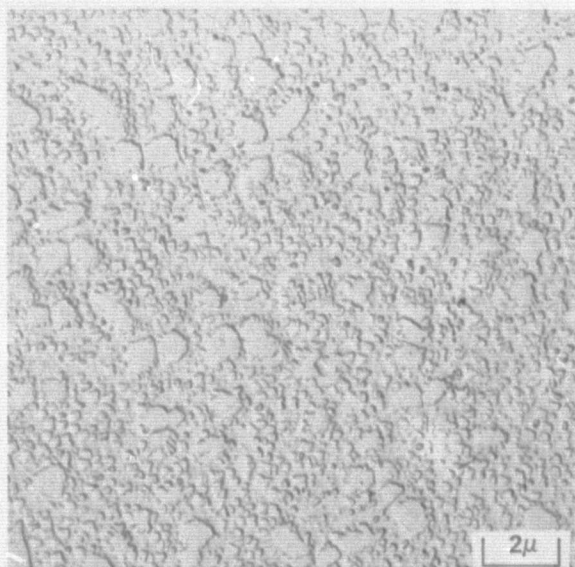
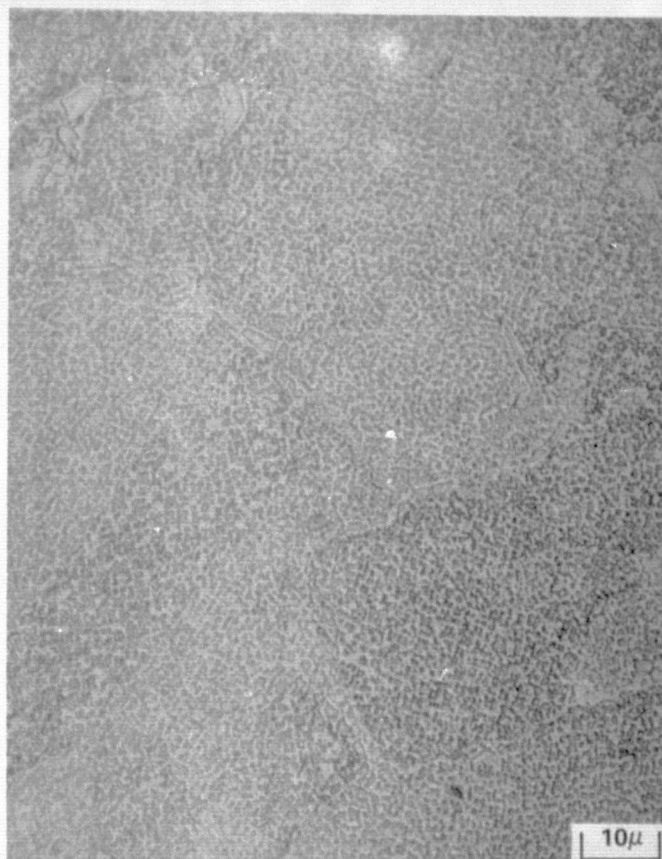


THICK

THIN

Figure 47 Micrographs of HIP Low Carbon Astroloy Heat Treated at 1116°C (2040°F)/2 hrs./AC + 871°C (1600°F)/8 hrs/AC Showing Precipitation of Cuboidal Gamma-Prime Approximately $0.3 - 0.5 \mu$ in size.

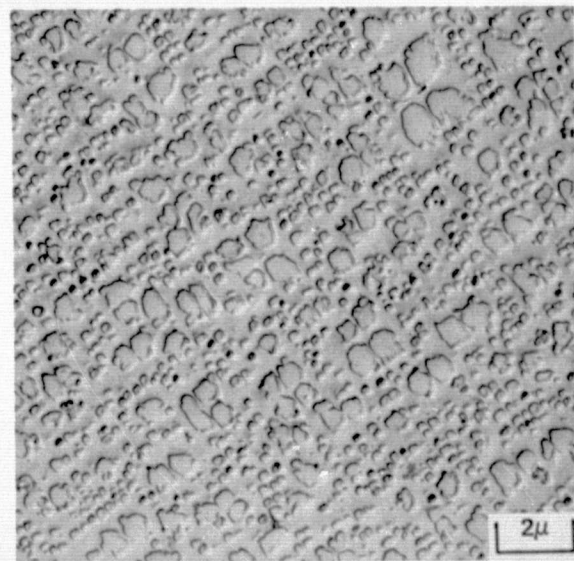
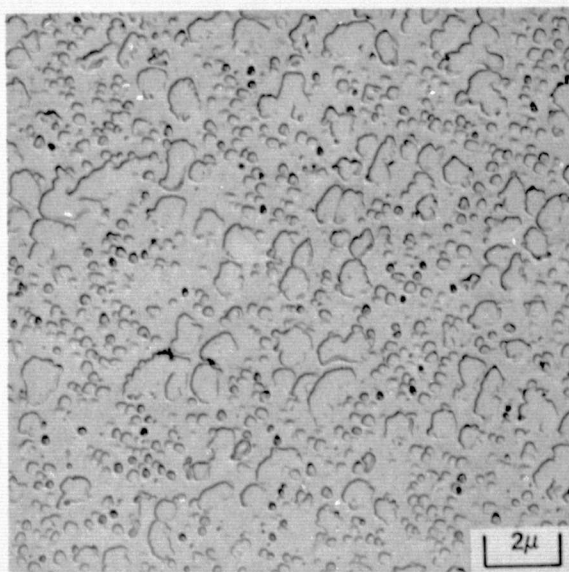
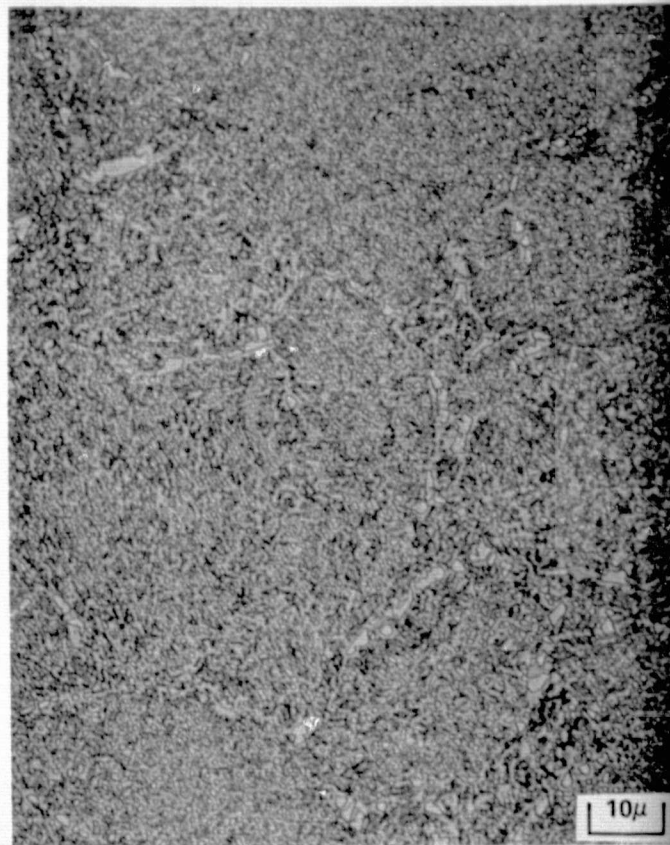
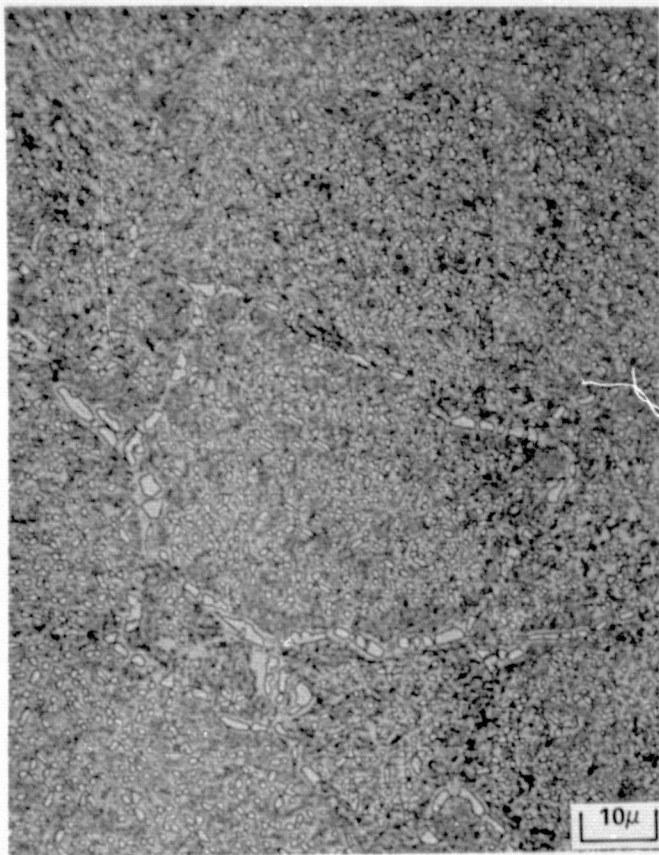
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THICK

THIN

Figure 48 Micrographs of HIP Low Carbon Astroloy Heat Treated at 1116°C (2040°F)/2 hrs/AC + 871°C (1600°F)/4 hrs/AC + 1800°F /4 hrs Showing Precipitation of Cuboidal Gamma-Prime approximately $0.3 - 0.5 \mu$ in size.



THICK

THIN

Figure 49 Micrographs of HIP Low Carbon Astroloy Heat Treated at 1116°C (2040°F)/2 hrs./AC + 871°C (1600°F)/8 hrs/AC + 980°C (1800°F)/4 hrs/AC + 649°C (1200°F)/24 hrs/AC. See Figure 50 for high magnification micrograph showing fine gamma-prime matrix precipitation approximately $0.05\ \mu$ in size.

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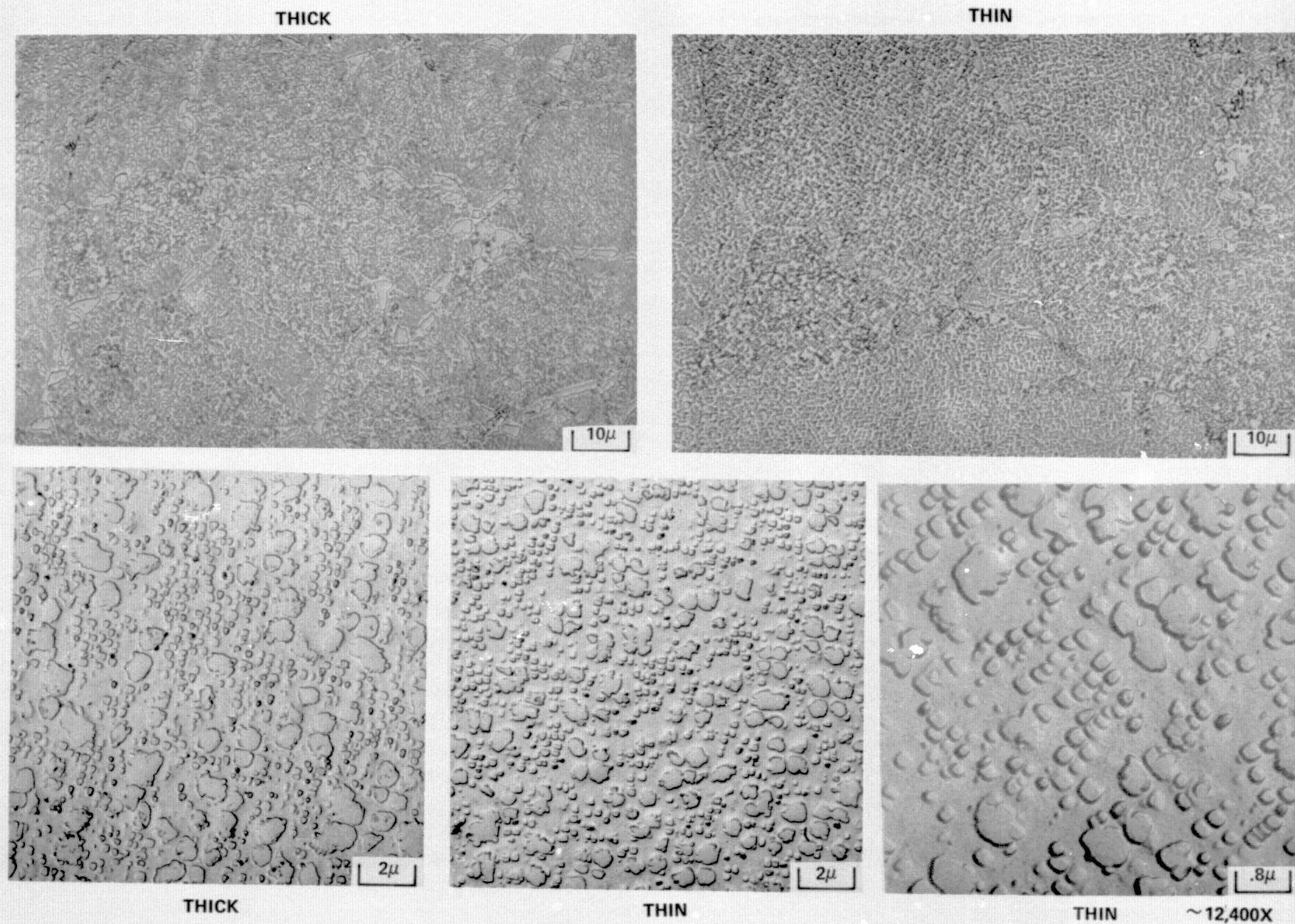


Figure 50 Micrographs of HIP Low Carbon Astroloy Heat Treated at 1116°C (2040°F)/2 hrs/AC + 871°C (1600°F)/4 hrs/AC + 649°C (1200°F)/24 hrs/AC + 760°C (1400°F)/8 hrs/AC Showing a Barely Resolvable Matrix Gamma-Prime Precipitation Approximately $0.05\text{ }\mu\text{m}$ in size (Lower Right). No significant microstructural differences could be observed between thick and thin sections.

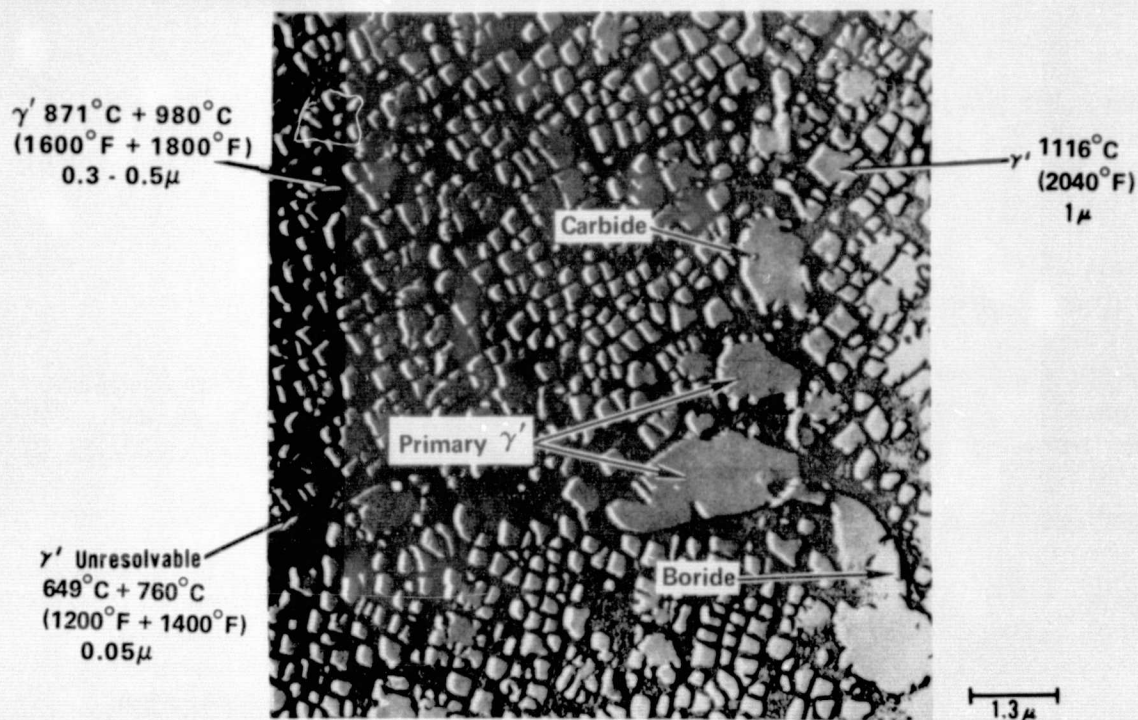


Figure 51 Electron Replica Micrograph of Low Carbon Astroloy Heat Treated at 1116°C (2040°F)/2 hrs/AC + 871°C (1600°F)/8 hrs/AC + 980°C (1800°F)/4 hrs/AC + 649°C (1200°F)/24 hrs/AC + 760°C (1400°F)/8 hrs/AC showing Minor Phases of Carbides and Borides and Fine Distinct Gamma-Prime Sizes.

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6.0 TASK IV – ENGINE DEMONSTRATION TEST

One direct HIP disk (50-2) was machined per P/N 767601 and installed in a land-based experimental engine for testing. The details of this engine test are classified as Category 2 – F.E.D.D. data and will be reported in Volume II (CR-135410).

7.0 TASK V – POST-TEST ANALYSIS

POST-ENGINE TEST ANALYSIS

The results of a post-test evaluation of the experimental engine-tested HIP disk are classified as Category 2 – F.E.D.D. data. This analysis which includes dimensional inspection of the HIP disk before and after the engine test is reported in Volume II of this contract (CR-135410).

ANALYSIS OF RESULTS

The primary objective of this program was to establish the manufacturing methods necessary to produce direct HIP turbine disks to an ultrasonically inspectable shape and with properties comparable to conventionally forged Waspaloy[®]. Manufacturing methods including powder manufacture, container design, powder handling, and HIP consolidation were established by the processing of five disks. Mechanical property testing and metallographic analysis (thermally induced porosity tests) of the integral test coupon ring of each disk was performed to determine the integrity of the product.

Dimensional analysis showed that each disk was large enough to yield a finish-machined disk component. The tooling modification for the last dimensional iteration was successful in bringing the as-HIP surface to well within <0.25 cm (.100 in.) of the sonic configuration. Ultrasonic inspection of the HIP near sonic configuration demonstrated sensitivity sufficient to resolve a machined standard defect as small as 1/64" (No. 1 flat-bottom hole) because of the fine grain, homogeneous microstructure. Current ultrasonic inspection technology for conventionally forged bill-of-material Waspaloy is performed at a resolution sensitivity equal to a machined 3/64" (No. 3) flat-bottom hole.

Machinability tests demonstrated that HIP low carbon Astroloy was similar to conventionally forged bill-of-material Waspaloy. A full-size direct-HIP consolidation was finish-machined with the same parameters as conventionally forged Waspaloy.

Based on the results of this manufacturing methods study, a process control plan and acceptance criteria were established as presented in Appendices A and B, respectively.

Two disks were characterized by more comprehensive testing to establish a proposed material specification. The tensile, stress-rupture and creep goals were met while an estimated design lower limit was established for notched ($K_t = 2.5$) low-cycle fatigue properties. These property goals were comparable to conventionally forged Waspaloy[®] goals. A proposed material specification which establishes the material capability is given in Appendix D.

Other objectives of this program were to reduce material input by 54.5 kg (120 lbs.) and cost by 20% as compared to bill-of-material conventionally forged Waspaloy®. The results of this comparison are given in Figure 52. Observations can be made as follows:

- A cost reduction of 25% was achieved comparing the 1974 cost (base at start of program) of a conventional Waspaloy® forging with 1978 HIP low carbon Astroloy cost.
- HIP low carbon Astroloy consolidation cost 8% less than conventional Waspaloy® forging cost in 1978.
- HIP low carbon Astroloy consolidations reduced raw material weight by 30% when compared to input weight of conventional Waspaloy® forgings.

FINAL RECOMMENDATIONS

Based upon the results of this program and related P&WA experience, direct HIP low carbon Astroloy disks are suitable for incorporation in commercial engines.

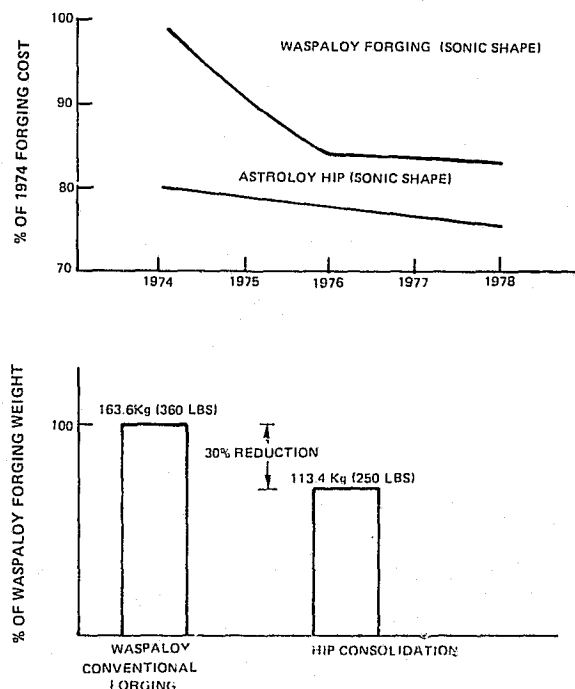


Figure 52 HIP Versus Forging Cost Study for JT8D First Turbine Disk

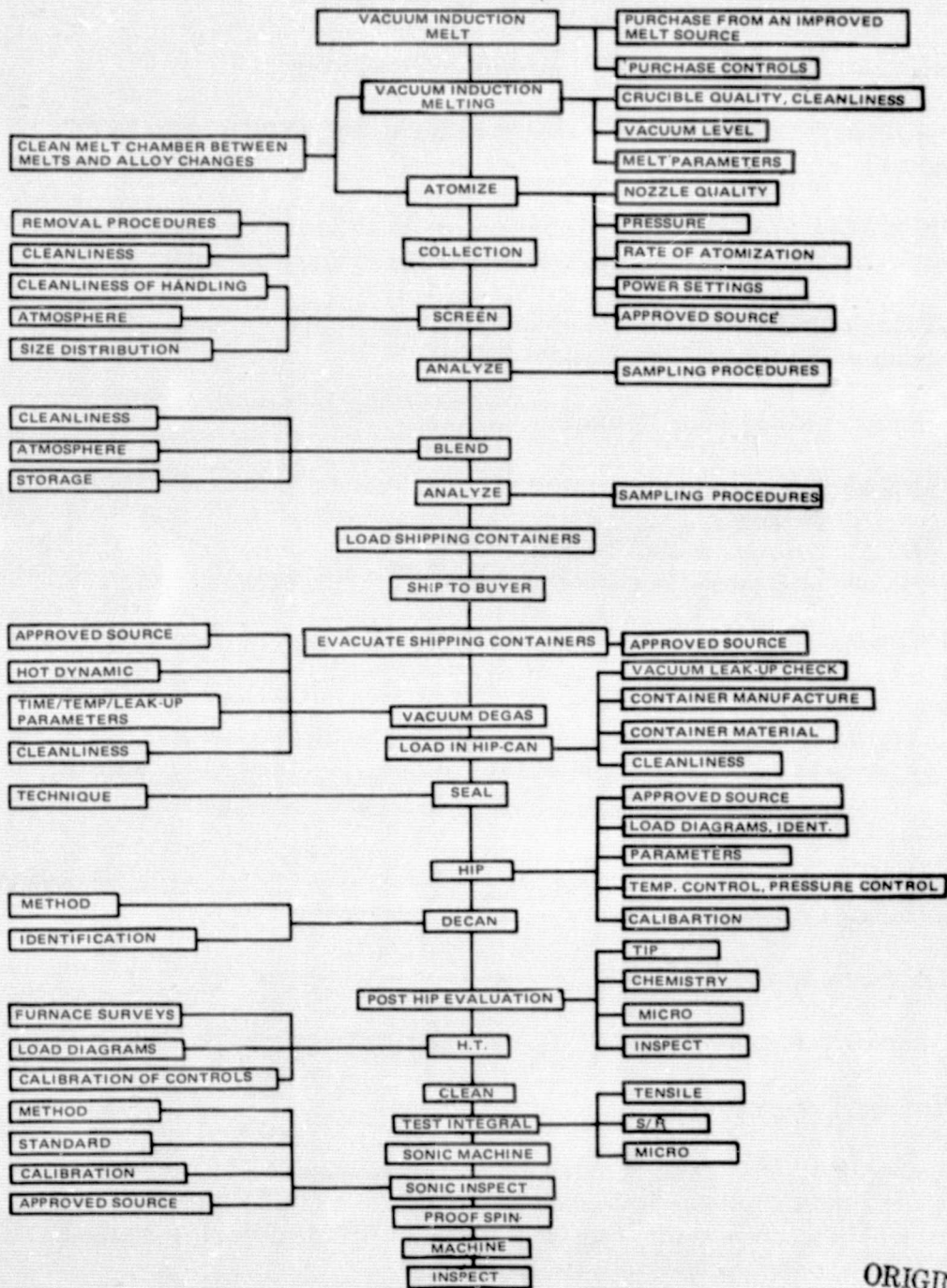
8.0 CONCLUSIONS

Based upon metallographic, ultrasonic, dimensional, chemical, and mechanical property analyses of HIP consolidated disks, conclusions are made as follows:

- (1) Suitable manufacturing methods were established for fabrication of direct-HIP low carbon Astroloy disk shapes for process verification. A process control plan, acceptance criteria, and material specifications were proposed.
- (2) Metallographic evaluation of TIP (thermally induced porosity) tested material is required to determine quality of HIP consolidations. Differences between porosity due to hollow particles and porosity due to container failure can be determined.
- (3) HIP sonic disk shapes with an as-heat treated surface can be ultrasonically inspected to a sensitivity equivalent to a .04cm (1/64") flat-bottom hole.
- (4) Dimensional inspection demonstrated that current container design produces as-HIP surfaces well within .25 cm (.100 in.) of target sonic shape.
- (5) Lathe turning (roughing and finishing) milling, drilling, boring and broaching tests showed that the machinability of direct HIP low carbon Astroloy is similar to conventionally forged Waspaloy®.
- (6) Stress-rupture and creep properties of direct HIP + heat treated low carbon Astroloy exceeded property goals while tensile properties met them. The property goals selected were comparable to conventionally forged Waspaloy®.
- (7) Tensile, stress-rupture, and creep properties of thin sections (rim) were slightly stronger than thick sections (bore). This may be attributed to cooling rate effects during solution and aging heat treatments.
- (8) A design lower limit curve was established for notched ($K_t = 2.5$) low-cycle fatigue calibration.
- (9) Reported oxygen gas content varies depending upon laboratory and gas standard used for calibration.
- (10) Direct HIP low carbon Astroloy disks reduced material weight by 54.5 kg (120 lbs.) and material costs by 25% as compared to conventionally forged Waspaloy® in 1974.

APPENDIX A

PROCESS CONTROL PLAN FOR POWDER ATOMIZATION/HIP PROCESS JT8D HIP FIRST TURBINE DISK



THE EXACT PARAMETERS OF EACH PROCESS STEP SHALL BE AGREED UPON BY PURCHASER AND VENDOR.

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Figure A-1 Process Control Plan

APPENDIX B

ACCEPTANCE CRITERIA FOR LOW CARBON ASTROLOY HIP CONSOLIDATIONS

1. SCOPE:
 - 1.1 Form: Hot isostatically pressed powder metallurgy product.
 - 1.2 Application: Primarily for rotor parts operating at temperatures up to 760°C (1400°F).
2. APPLICABLE DOCUMENTS: The following publications form a part of this specification to the extent specified herein; the latest issue shall apply:
 - 2.1 SAE Publications: Available from Society of Automotive Engineers, Inc., 400 Commonwealth Drive, Warrendale, PA 15096.
 - 2.1.1 Aerospace Material Specifications:
 - AMS 2269 Chemical Check Analysis Limits, Wrought Nickel and Nickel Base Alloys
 - AMS 2350 Standards and Test Methods
 - AMS 2630 Ultrasonic Inspection
 - 2.2 ASTM Publications: Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, PA 19103.
 - ASTM E112 Estimating Average Grain Size of Metals
 - ASTM E354 Chemical Analysis of High-Temperature, Electrical, Magnetic, and Other Similar Iron, Nickel, and Cobalt-Base Alloys
 - 2.3 Government Publications: Available from Commanding Officer, Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, PA 19120.
 - 2.3.1 Federal Standards:
 - Federal Test Method Standard No. 151 - Metals; Test Methods
3. Technical Requirements:
 - 3.1 Composition: Shall conform to the following percentages by weight, determined by wet chemical methods in accordance with ASTM E354, by spectrographic methods in accordance with Federal Test Method Standard No. 151, Method 112, or by other approved analytical methods.

	min		max
Carbon	0.02	—	0.04
Manganese	—		0.15
Silicon	—		0.20
Phosphorous	—		0.015
Sulfur	—		0.015
Chromium	14.00	—	16.00
Cobalt	16.00	—	18.00
Molybdenum	4.50	—	5.50
Titanium	3.35	—	3.65
Aluminum	3.85	—	4.15
Boron	0.015	—	0.025
Zirconium			0.06
Tungsten	—		0.05
Iron	—		0.50
Copper	—		0.10
Lead	—		0.0010 (10 ppm)
Bismuth	—		0.00005 (0.5 ppm)
Oxygen	—		0.010 (100 ppm)
Nitrogen	—		0.0050 (50 ppm)
Nickel	remainder		

3.1.1 Check Analysis: Composition variations shall meet the requirements of AMS 2269.

3.2 Thermally Induced Porosity: A sample of the product shall be heated to temperature within the range of 1204° - 1218°C (2200° - 2225°F), held at the selected temperature 8°C (± 15°F) for 4 hr., and air cooled. Microstructure after thermal exposure shall conform to the requirements agreed upon by purchaser and vendor.

3.3 Ultrasonic Inspection: The HIP consolidation shall undergo ultrasonic inspection in accordance with ASTM 2630 using a standard agreed upon by purchaser and vendor.

3.4 Dimensional Inspection: The HIP consolidation shall undergo dimensional inspection with the data conforming to the requirements agreed upon by purchaser and vendor.

3.5 Condition: The product shall be supplied as solution, stabilization, and precipitation heat treated and descaled as follows.

3.6 Heat Treatment:

3.6.1 Solution Heat Treatment: Heat to a temperature within the range 1080° - 1135°C (1975° - 2075°F), hold at this selected temperature within ± 8°C (± 15°F) for 2 - 4 hr, and cool at a rate equivalent to air cool.

3.6.2 Stabilization Heat Treatment: Heat to 870° ± 8 (1600°F ± 15), hold at heat for 8 hr., and cool to room temperature at a rate equivalent to air cool; heat to 982°C ± 8 1800°F ± 15, hold at heat for 4 hr., and cool at a rate equivalent to air cool.

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3.6.3 Precipitation Heat Treatment: Heat to $650^{\circ}\text{C} \pm 8$ ($1200^{\circ}\text{F} \pm 15$), hold at heat for 24 hr., and air cool to room temperature, heat to $760^{\circ}\text{C} \pm 8$ ($1400^{\circ}\text{F} \pm 15$), hold at heat for approximately 8 hr., and air cool.

3.7 Integral Test Specimens: Shall be located so as to approximate thickest cross-sectional area and slowest cooling rate from hot isostatic pressing and heat treatment, as agreed upon by the purchaser and the vendor. Alternate location of integral test specimens and their properties shall be as agreed upon by the purchaser and the vendor.

3.7.1 Tensile Properties: Tensile test specimens cut from the product and tested at the temperatures indicated shall conform to the following requirements. Specimens to be tested at $538^{\circ}\text{C} \pm 5$ ($1000^{\circ}\text{F} \pm 10$) shall be held at heat for 30 min. prior to testing. Rate of strain for testing at $538^{\circ}\text{C} \pm 5$ ($1000^{\circ}\text{F} \pm 10$) shall be maintained at approximately 0.005 mm per mm per min. (0.005 in. per in. per min.) to the 0.2% yield strength.

	Room Temperature	$538^{\circ}\text{C} \pm 5$ ($1000^{\circ}\text{F} \pm 10$)
Tensile Strength, MPa, (psi), min	1,241 (180,000)	1,103 (160,000)
Yield Strength, at 0.2% Offset, MPa (psi), min	862 (125,000)	758 (110,000)
Elongation, % in 4D, min	15	15
Reduction of Area, %, min	18	18

3.7.2 Stress-Rupture Properties at 732°C (1350°F): A combination smooth and notched test specimen machined to the dimensions shown in Figure B-1 and Table I, maintained at $732^{\circ}\text{C} \pm 3$ ($1350^{\circ}\text{F} \pm 5$) under continuously applied axial stress of 552 MPa 80,000 psi shall not rupture in less than 23 hours. The test shall be continued to rupture with fracture occurring in the smooth section. Elongation of the smooth section after rupture, measured at room temperature, shall be not less than 8% in 4D.

3.7.2.1 As an alternate procedure, separate smooth and notched test specimens, machined from adjacent sections of the same piece with gage sections conforming to the respective dimensions of Table I may be tested individually, under the above conditions. The smooth specimen shall not rupture in less than 23 hr. and elongation after rupture, measured at room temperature, shall be not less than 8% in 4D. The notched specimens shall not rupture in less time than the smooth specimen.

3.7.3 Microstructure: Shall conform to requirements agreed upon by purchaser and the vendor.

3.7.4 Grain Size: Average shall be 4 or finer as determined by Planimetric Procedure in ASTM E112.

4. REJECTIONS: Material not conforming to this acceptance criteria or to authorized modification will be subject to rejection.

TABLE I (SI)

Specimen Number	Center Gage Diameter G, Millimeter	C	D, min	E, min	F	H	RR
1	3.18	3.18	12.70	9.53	3.18	4.50	0.10
2	3.81	3.18	15.24	9.53	3.81	5.38	0.13
3	4.06	3.18	16.51	9.53	4.06	5.74	0.13
4	4.52	3.18	19.05	9.53	4.52	6.35	0.16
5	6.40	3.18	25.40	9.53	6.40	9.07	0.23
6	9.07	3.18	38.10	9.53	9.07	12.70	0.30
Tolerance	± 0.03	± 1.59	—	—	± 0.03	± 0.08	± 0.013

TABLE I

Specimen Number	Center Gage Diameter G, Inch	C	D, min	E, min	F	H	RR
1	0.125	0.125	0.500	0.375	0.125	0.177	0.004
2	0.150	0.125	0.600	0.375	0.150	0.212	0.005
3	0.160	0.125	0.650	0.375	0.160	0.226	0.005
4	0.178	0.125	0.750	0.375	0.178	0.250	0.006
5	0.252	0.125	1.000	0.375	0.252	0.357	0.009
6	0.357	0.125	1.500	0.375	0.357	0.500	0.012
Tolerance	± 0.001	± 0.062	—	—	± 0.001	± 0.003	± 0.0005

- Note 1. Radius "R" between gage and full diameter sections and between full section and thread sections shall be 0.125 - 0.250 inch (3.18 - 6.35 mm).
- Note 2. Finish specimens to $\sqrt{16}$ (0.4 micrometers) or better on all "f" surfaces; surface roughness of notch root radius shall be substantially the same as on sides of notch as determined by examination at 10X magnification.
- Note 3. The difference between dimensions "F" and "G" shall not exceed 0.0005 in. (0.013 mm) for specimens 1, 2, 3, and 4 and shall not exceed 0.001 in. (0.03 mm) for specimens 5 and 6.
- Note 4. Taper gage length "D" to center so that diameter "G" at the ends of the gage length exceeds diameter "G" at the center of the gage length by 0.0005-0.0015 in. (0.013 - 0.038 mm).
- Note 5. All sections shall be concentric about specimen axis within 0.001 inch (0.03 mm).
- Note 6. Thread size "T" shall be such that minor diameter of the thread is greater than "H".
- Note 7. Thread length "B" shall be equal to or greater than "T".
- Note 8. Dimension "A" is not specified.
- Note 9. Specimens 3 and 4 are the preferred specimens.

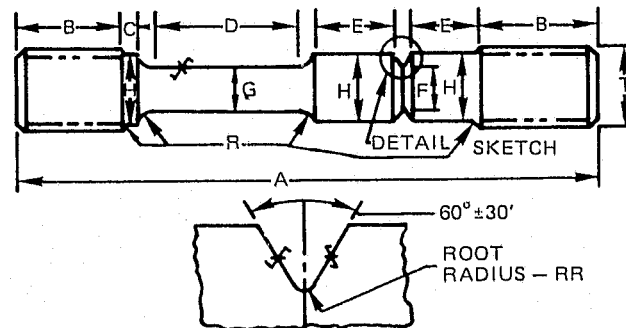


Figure B-1 Combination Smooth-and-Notched Test Stress-Rupture Specimen

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APPENDIX C

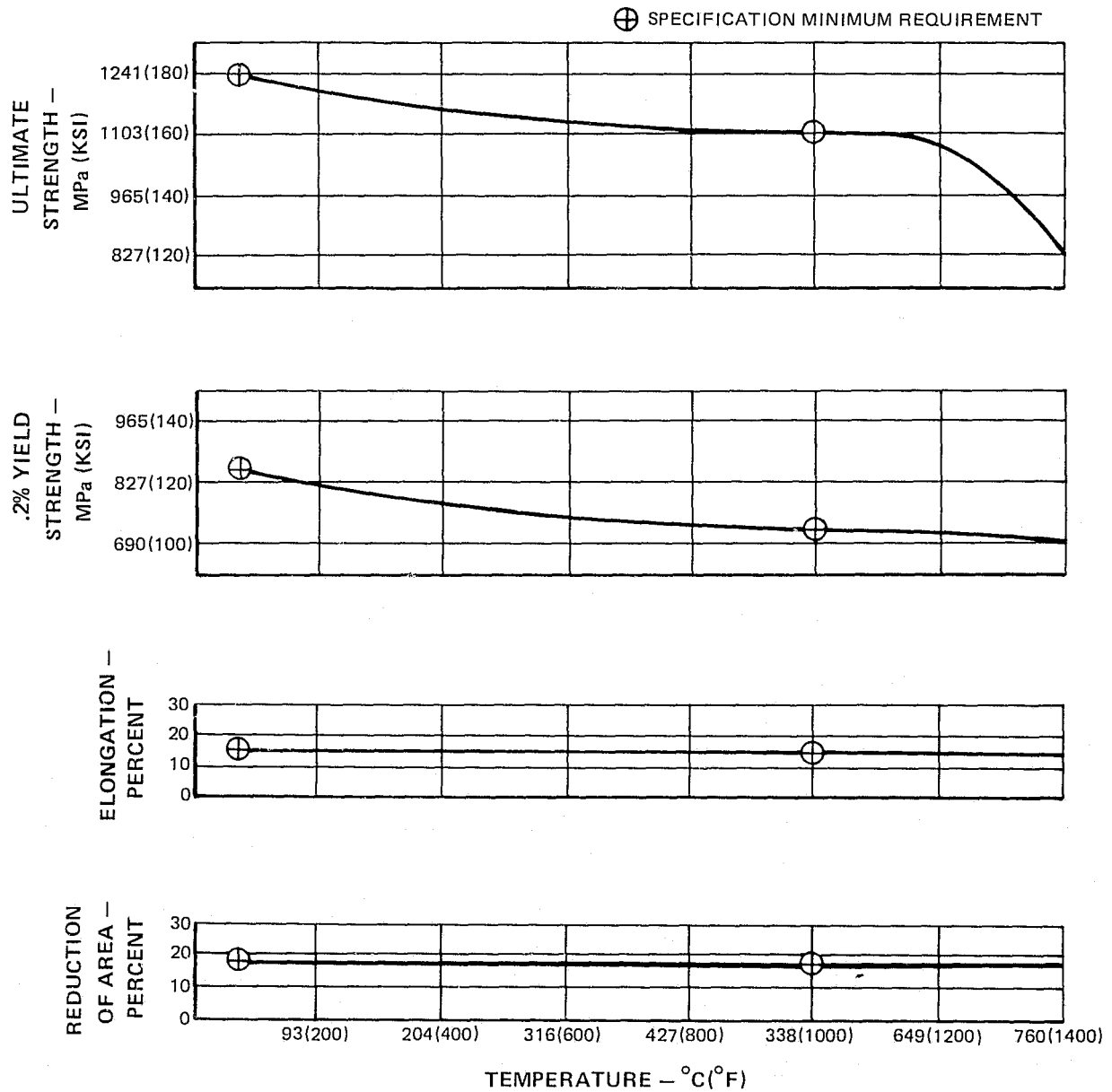
PROCEDURE FOR ROUND-ROBIN OXYGEN AND NITROGEN GAS ANALYSIS

1. Prepare samples to be analyzed using normal procedures, and report this sample preparation procedure. No sample preparation is necessary for the oxygen and nitrogen standards supplied.
2. Do not use platinum or any other flux in these analyses.
3. Use LECO-MODEL TC 30/TC 36 Analyzer.
4. Calibrate equipment to exactly 34 ppm nitrogen using standard (34 $\pm$ 5) supplied.
5. Analyze three additional nitrogen standards (34 $\pm$ 5) supplied and report these three values. These values should be within 34 $\pm$ 5 ppm nitrogen. If not, repeat steps 4 and 5 until 34 $\pm$ 5 ppm nitrogen is attained for three consecutive analyses.
6. Calibrate equipment to exactly 111 ppm oxygen using standard (111 $\pm$ 6) supplied.
7. Analyze three additional oxygen standard (111 $\pm$ 6) supplied and report these three values. These values should be within 111 $\pm$ 6 ppm oxygen. If not, repeat steps 6 and 7 until 111 $\pm$ 6 ppm oxygen is attained for three consecutive analyses.
8. Analyze each sample (total of four) for oxygen and nitrogen content and report results.
9. Analyze three additional oxygen standards (111 $\pm$ 6) and three nitrogen standards (34 $\pm$ 5) supplied and report these results.

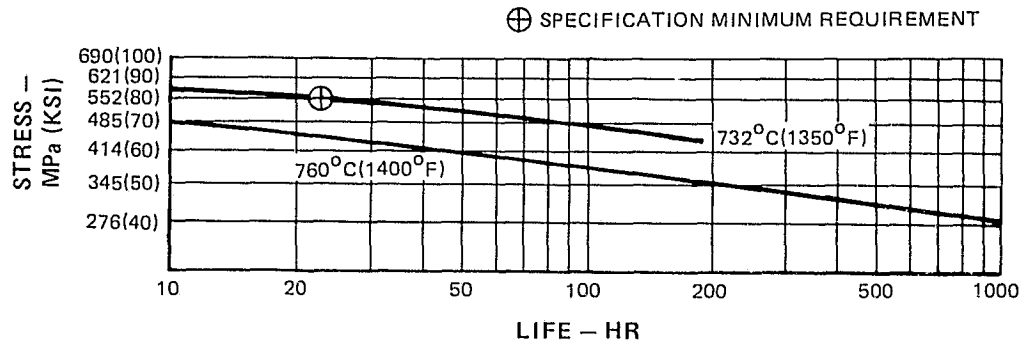
APPENDIX D

MATERIAL SPECIFICATION SHOWING LOWER LIMIT CURVES FOR HIP CONSOLIDATED LC ASTROLOY

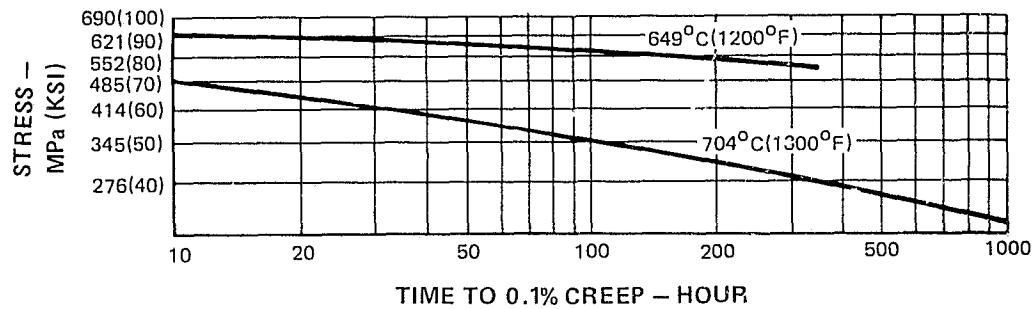
TENSILE PROPERTIES



STRESS – RUPTURE STRENGTH



0.1% CREEP STRENGTH



NOTCHED ($K_t = 2.5$) LOW-CYCLE FATIGUE PROPERTIES

